BNL Physics Seminar
January 24, 2002

Search for $K^+ \to \pi^+ \nu \bar{\nu}$ at low momentum

- Motivation
- The experiment
- Data analysis
- Backgrounds
- Future
- Conclusion

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E787

A Search for $K^+ \to \pi^+ \nu \bar{\nu}$ and Related Decays

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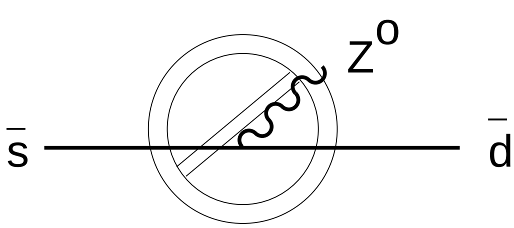
Consequences of Cabibbo - Kobayashi - Maskawa Mixing

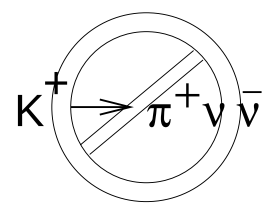
neutral currents:

$$\begin{pmatrix} d' & s' & b' \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} d & s & b \end{pmatrix} \underbrace{V^\dagger V}_{I} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Longrightarrow$$

$$ddZ + ssZ + bbZ + uuZ + ccZ + ttZ$$

No “flavor-changing neutral currents”





Similarly following decays are not allowed

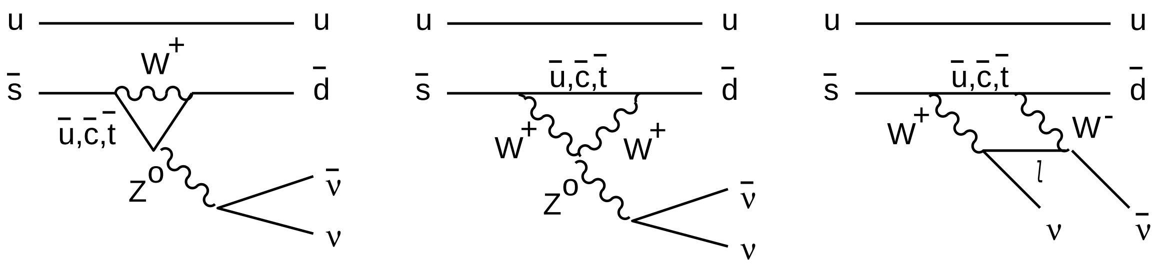
$K_L \to \mu^+\mu^-$

$K_L \to e^+e^-$

$K^+ \to \pi^+\mu^+\mu^-$

... etc.

... or are they? Each of these diagrams *is* allowed:



$V_{us}^*,\ V_{cs}^*,\ V_{ts}^*$ $\qquad$ $V_{ud},\ V_{cd},\ V_{td}$

Unitarity of $V \implies$ "G.I.M. mechanism"

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$$

No flavor-changing neutral currents at all!

Loophole: $m_u \ll m_c \ll m_t$: the cancellation is not exact and most of the surviving rate is due to **top quarks!**

The residual rate is calculable – for three neutrino flavors:

$$\mathrm{BR}_{\mathrm{calc}}(K^+ \to \pi^+ \nu \bar{\nu}) = (0.75 \pm 0.29) \times 10^{-10}$$

A.J. Buras, Preprint hep-ph/0101336

CP and $\pi\nu\bar{\nu}$

$$K_L = \frac{K_2+\epsilon K_1}{\sqrt{(1+|\epsilon|^2)}} \quad CP \approx -1$$
$$K_S = \frac{K_1+\epsilon K_2}{\sqrt{(1+|\epsilon|^2)}} \quad CP \approx +1$$

$\pi^0\nu\bar{\nu}$ is CP even state

$$\begin{array}{lll} A(K^0 \to \pi^0\nu\bar{\nu}) & = (1/\sqrt{2})A(K^+ \to \pi^+\nu\bar{\nu}) & \\ A(K_1 \to \pi^0\nu\bar{\nu}) & = Re(A(K^+ \to \pi^+\nu\bar{\nu})) & = R \\ A(K_2 \to \pi^0\nu\bar{\nu}) & = iIm(A(K^+ \to \pi^+\nu\bar{\nu})) & = iI \\ B(K_L \to \pi^0\nu\bar{\nu}) & = I^2 + 2Re(-i\epsilon RI) + |\epsilon|^2R^2 & \simeq I^2 \end{array}$$

$$R/I \simeq Re(V_{ts}^*V_{td})/Im(V_{ts}^*V_{td}) \simeq \frac{3.0\times10^{-4}}{1.4\times10^{-4}}$$

But the smallness of $|\epsilon| \sim 0.0022$ makes $K_L \to \pi^0\nu\bar{\nu}$ almost entirely through direct CP violation ($K_2 \to \pi^0\nu\bar{\nu}$).
Littenberg, 1989

Measurements of $K \to \pi\nu\bar{\nu}$ provide CKM parameters with small theoretical uncertainties, but the experiments are hard.

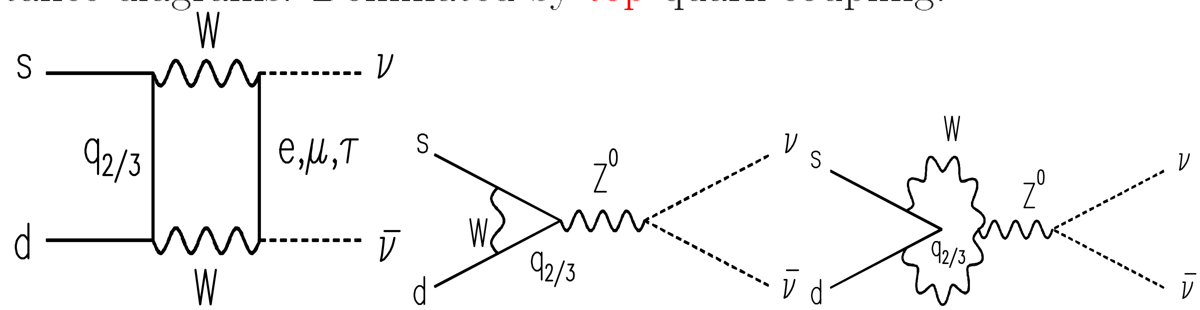
Extend analysis to get limit on branching ratio:

$$B(K_L \to \pi^0\nu\bar{\nu}) < 4.4 \times B(K^+ \to \pi^+\nu\bar{\nu})$$

Grossman and Nir, 1997

CKM and $\pi\nu\bar{\nu}$

"Golden" modes for determining CKM triangle. Dominated by short distance diagrams. Dominated by top quark coupling.



Hadronic matrix element well determined by $K^+ \to \pi^0 e^+ \nu_e$ decay.

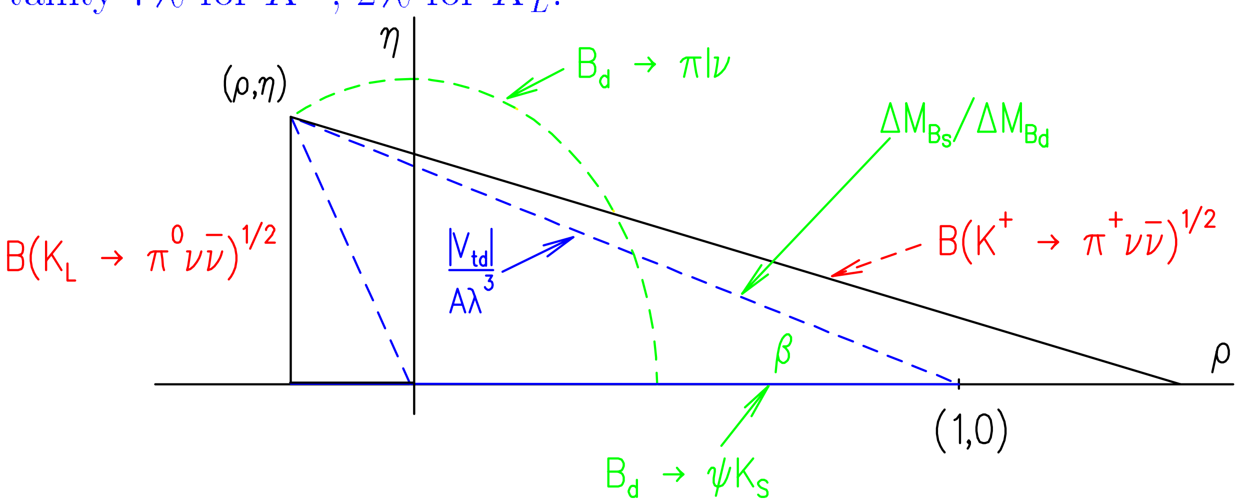
$$\mathrm{B}(K_L^\circ \to \pi^\circ \nu\overline{\nu}) = \frac{\tau_L}{\tau_{K^+}} \frac{\kappa_L \alpha^2 B(K_{e3})}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \Sigma_l \, |Im(V_{ts}^* V_{td}) X(x_t)|^2$$

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) = \frac{\kappa_+ \alpha^2 B(K_{e3})}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \Sigma_l \, |X(x_t) V_{ts}^* V_{td} + X^l(x_c) V_{cs}^* V_{cd}|^2$$

$$\begin{aligned}
\mathrm{B}(K_L^\circ \to \pi^\circ \nu\overline{\nu}) &= 4.08 \times 10^{-10} A^4 \eta^2 \\
&= (2.6 \pm 1.2) \times 10^{-11} \\
\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) &= 8.88 \times 10^{-11} A^4 [(\overline{\rho}_0 - \overline{\rho})^2 + (\sigma\overline{\eta})^2] \\
&= (7.5 \pm 2.9) \times 10^{-11} \ ,
\end{aligned}$$

$$\sigma = (1 - \tfrac{\lambda^2}{2})^{-2}; \ \overline{\rho}_0 = 1.4$$

Uncertainties from current CKM parameters. Intrinsic theoretical uncertainty 7% for K^+, 2% for K_L.



[0] Milind V. Diwan

Measurement at low momentum ?

- Current observation based on two events with $P > 211 MeV/c$.

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$$

S. Adler et al., Phys. Rev. Lett. 88, 041803 (2002).

- Tension between $B(K^+ \to \pi^+ \nu\bar{\nu})$ and $B_d - \bar{B}_d$ mixing.

  Need measurement with higher statistics for $K^+ \to \pi^+ \nu\bar{\nu}$ and $\Delta M_{B_d}/\Delta M_{B_s}$

- Exotic physics possibilities such as $K^+ \to \pi^+ X^0$ where X^0 has some mass need to be examined.

- Sizable SUSY contributions to $s \to d\nu\bar{\nu}$ allowed because $K_L \to \mu^+\mu^-$ and ϵ'/ϵ do not provide sufficient constraint. Also correlations exist with $b \to dl^+l^-$ and $b \to sl^+l^-$.

  G. D'Ambrosio and G. Isidori, hep-ph/0112135

- Other exotic physics could modify the spectrum.

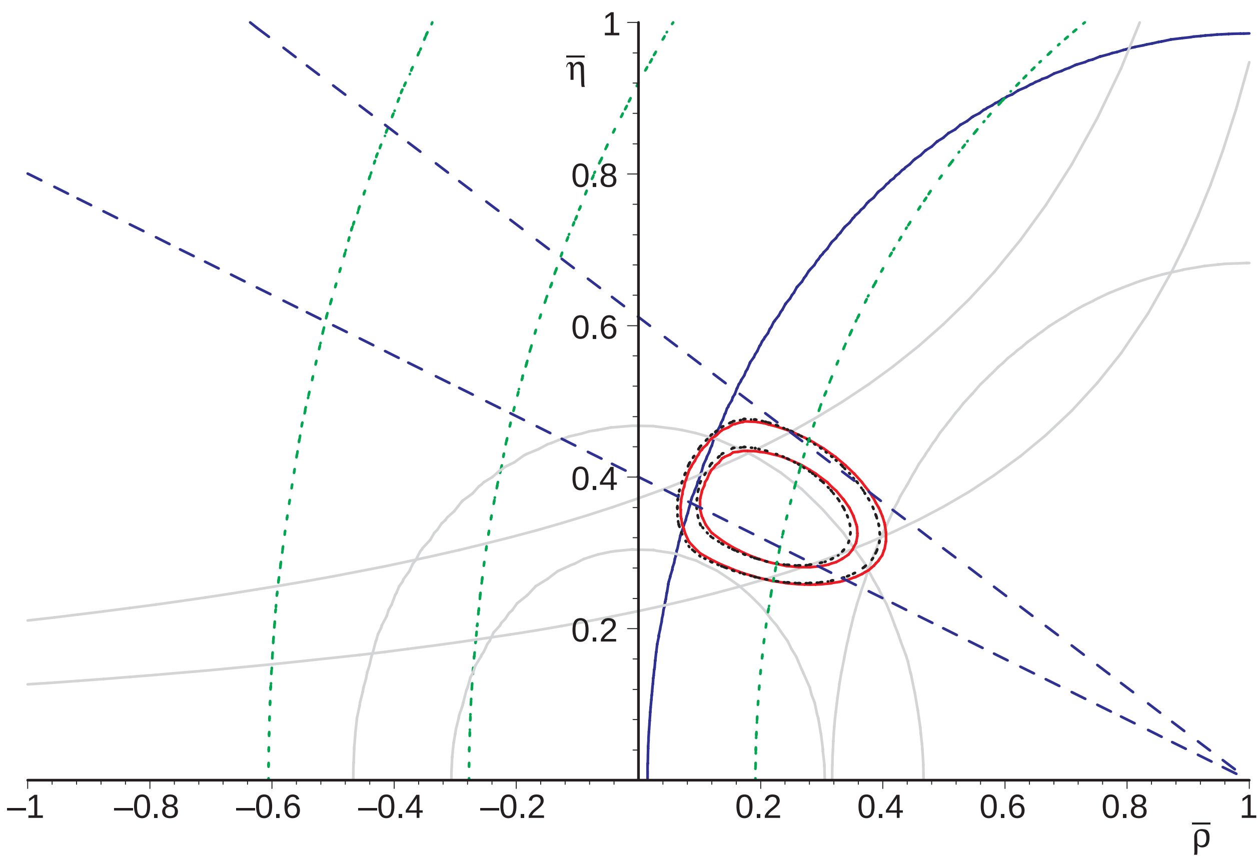
$$K^+ \to \pi^+ JJ$$

  Bertolini and Sanatamaria, NP **B315**, 558 (1989).

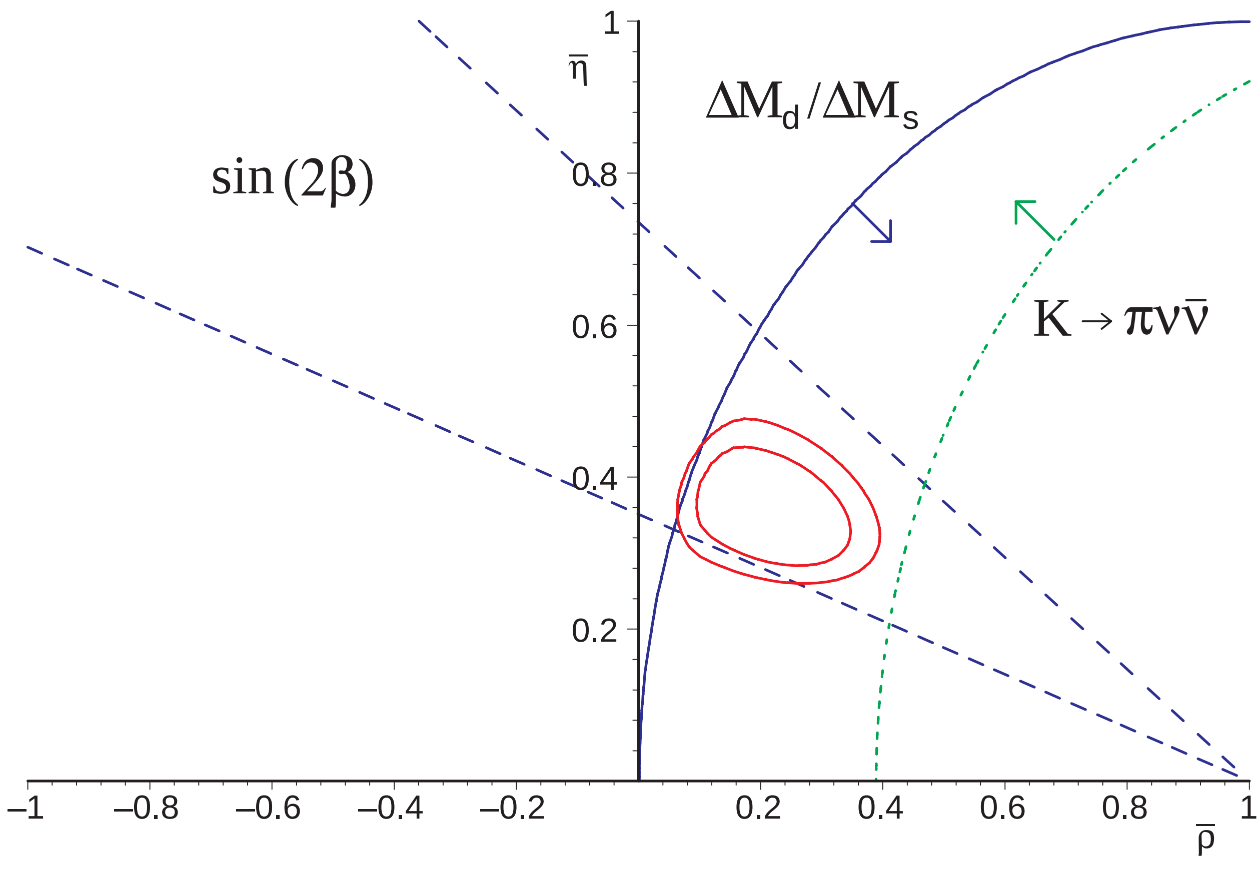
- Within SM long-distance physics ($\sim 10^{-13}$) could have a distorted spectrum.

  Rein and Sehgal, PRD **39**, 3325 (1989).

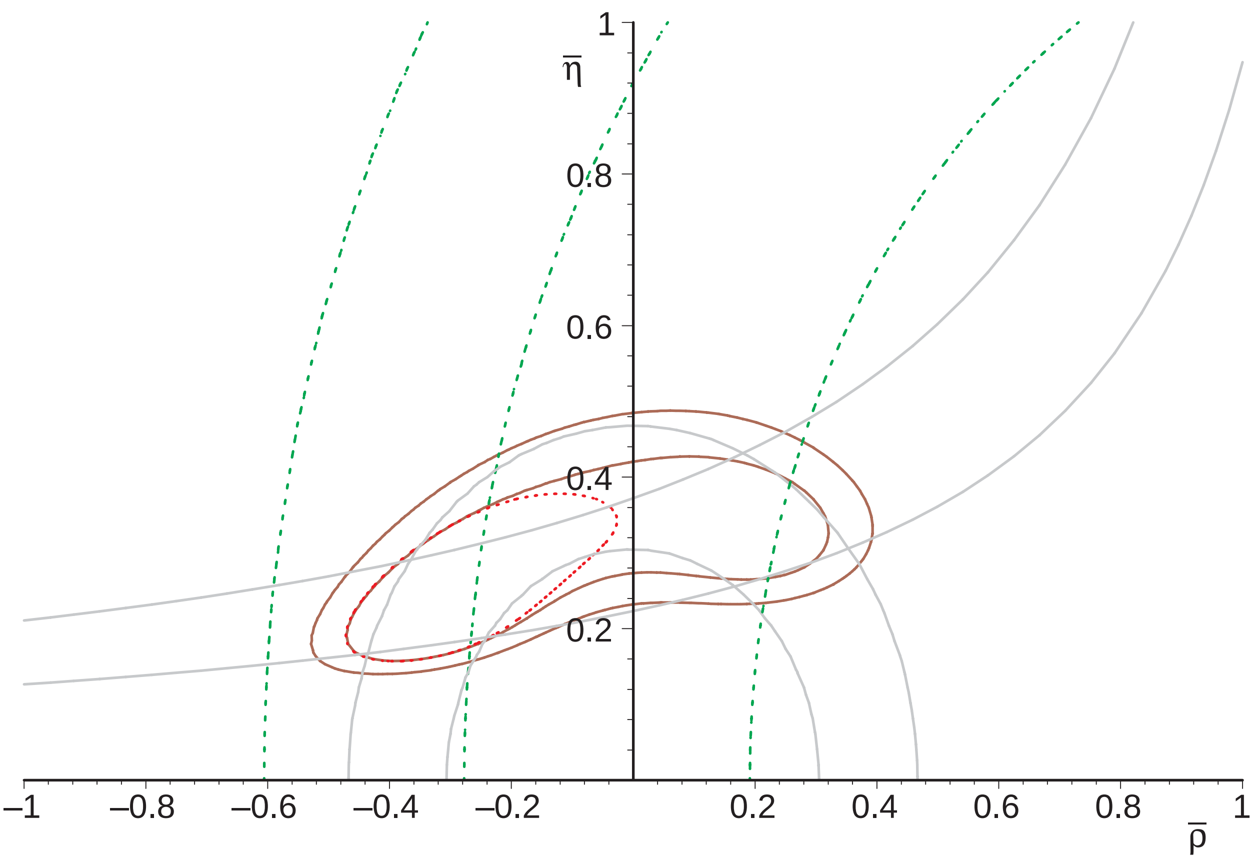
- Attempt to enhance the efficiency for $K^+ \to \pi^+ \nu\bar{\nu}$ over all phase phase-space.



1
η̄
0.8
0.6
0.4
0.2
–1
–0.8
–0.6
–0.4
–0.2
0.2
0.4
0.6
0.8
1
ρ̄

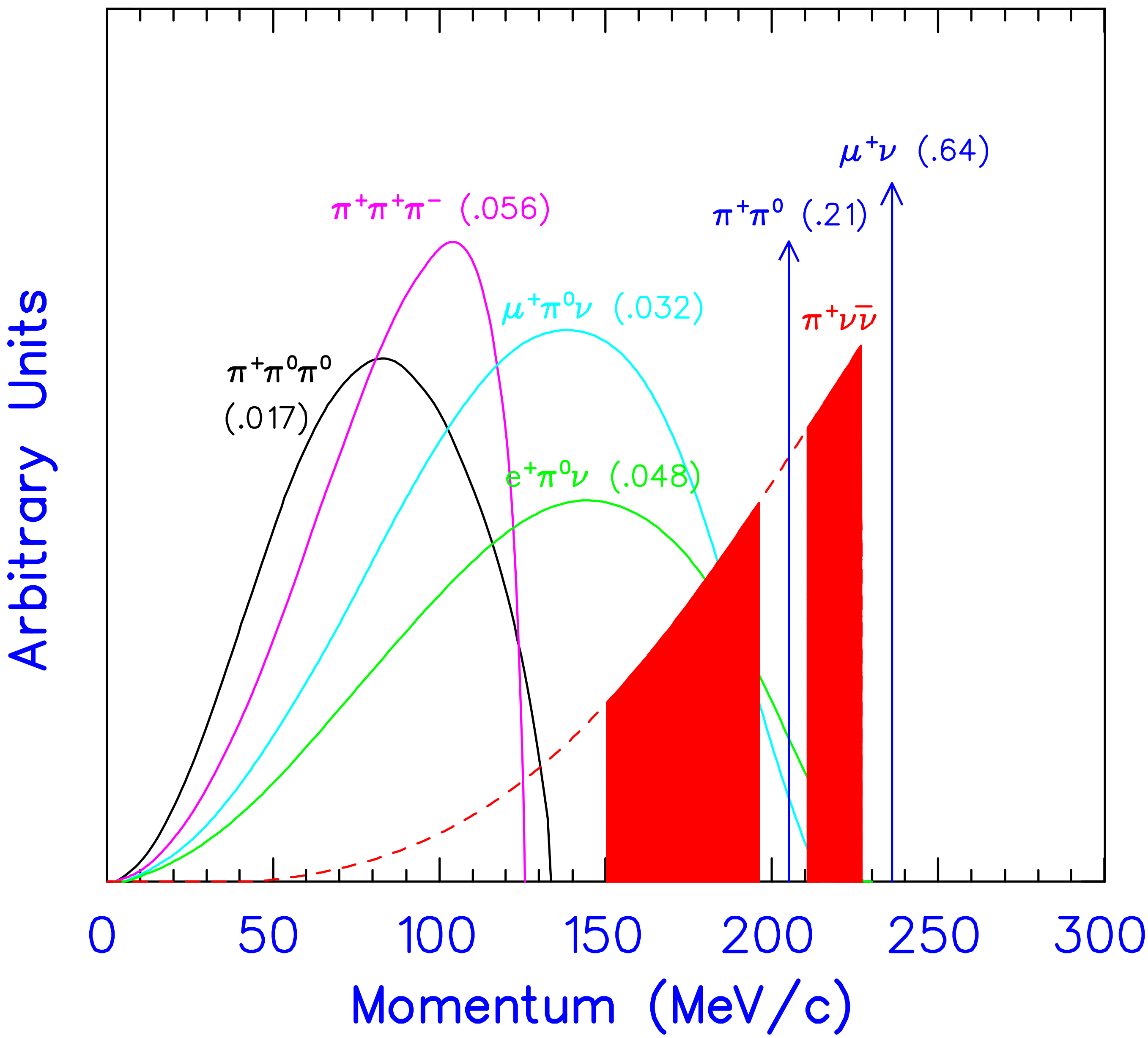


$\bar{\eta}$
1
0.8
0.6
0.4
0.2
$\Delta M_d/\Delta M_s$
$\sin(2\beta)$
$K \to \pi\nu\bar{\nu}$
–1
–0.8
–0.6
–0.4
–0.2
0.2
0.4
0.6
0.8
1
$\bar{\rho}$



1
$\bar{\eta}$
0.8
0.6
0.4
0.2
–1
–0.8
–0.6
–0.4
–0.2
0.2
0.4
0.6
0.8
1
$\bar{\rho}$

PNN backgrounds and tools

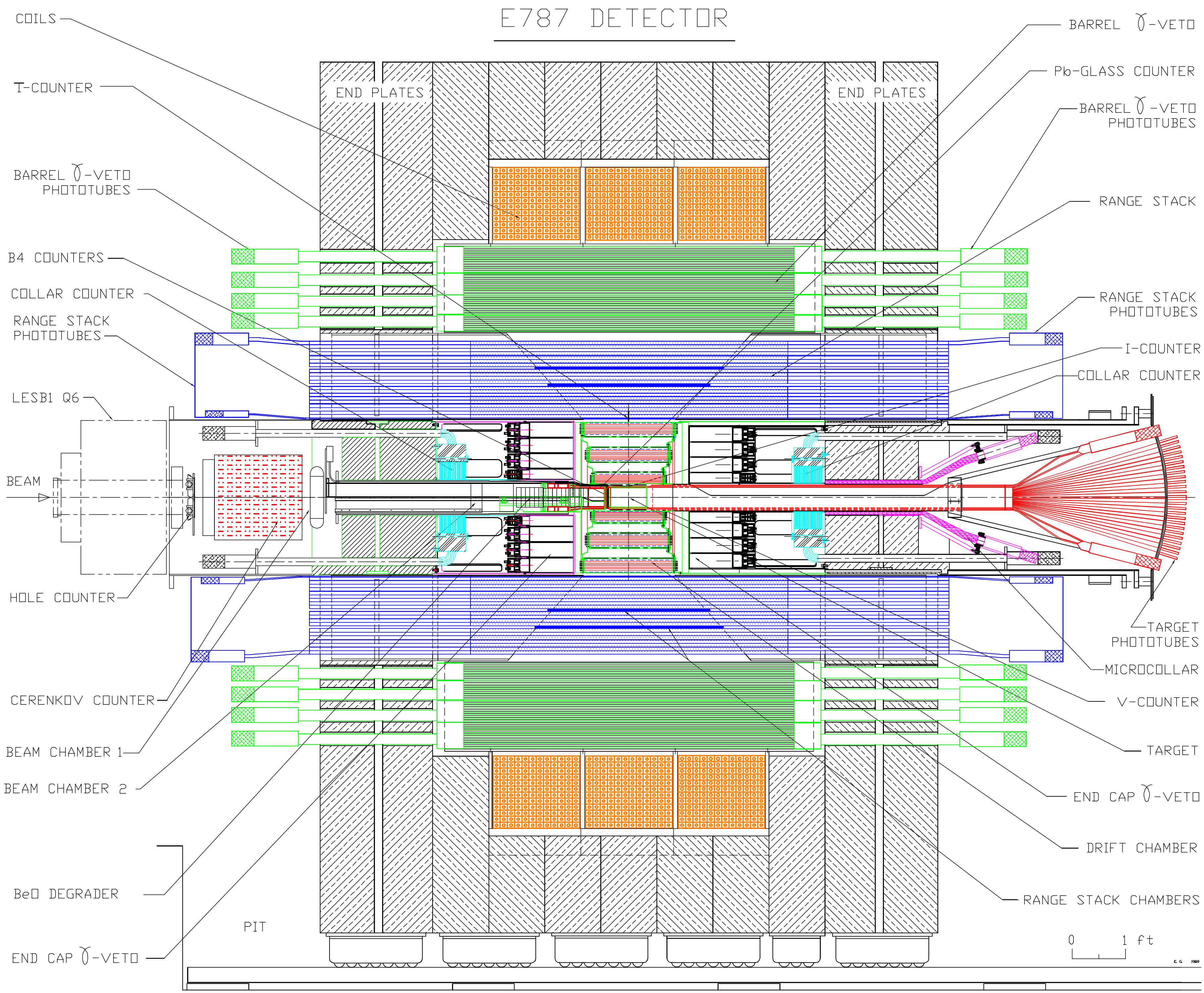


PNN1 main backgrounds

- $K^+ \to \pi^+\pi^0$: Two body kinematics and Photon veto
- $K^+ \to \mu^+\nu$: Two body kinematics and $\pi^+ \to \mu^+ \to e^+$ id.
- Scattering of π^+ contamination: K^+ decay time and Cerenkov Particle identification in the beam.

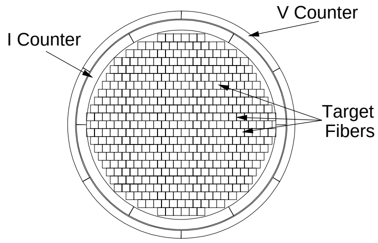
PNN2 main backgrounds

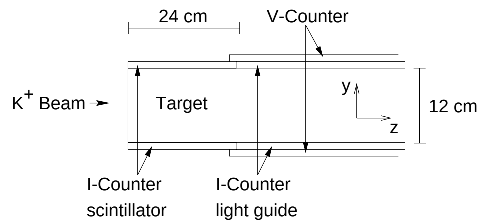
- $K^+ \to \pi^+\pi^0$ with scattering of π^+ in the kaon stopping target: Two body kinematics, Photon veto, and Detection of π^+ scattering in the target.
- $K^+ \to \pi^+\pi^-e^+\nu$: Detection of π^- and e^+ in the target.
- Scattering of π^+ contamination in the beam: K^+ decay time and Cerenkov Particle identification in the beam.
- Use CCD's to find π^+ hits hidden under the kaon fibers. Allow long kaon decay time to help.
- Photon veto system not as effective as for PNN1 because π^0 is not back-to-back with π^+.


E787 DETECTOR
COILS
T-COUNTER
BARREL γ-VETO PHOTOTUBES
B4 COUNTERS
COLLAR COUNTER
RANGE STACK PHOTOTUBES
LESB1 Q6
BEAM
HOLE COUNTER
CERENKOV COUNTER
BEAM CHAMBER 1
BEAM CHAMBER 2
BeO DEGRADER
END CAP γ-VETO
PIT
END PLATES
END PLATES
BARREL γ-VETO
Pb-GLASS COUNTER
BARREL γ-VETO PHOTOTUBES
RANGE STACK
RANGE STACK PHOTOTUBES
I-COUNTER
COLLAR COUNTER
TARGET PHOTOTUBES
MICROCOLLAR
V-COUNTER
TARGET
END CAP γ-VETO
DRIFT CHAMBER
RANGE STACK CHAMBERS
0 1 ft

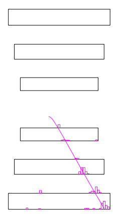
E787 Technique

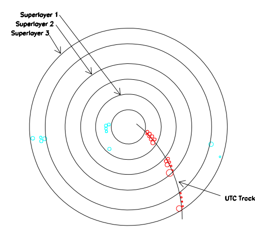
K^+ I.D.'d by beam counters, stop in 400-element sci-fi target



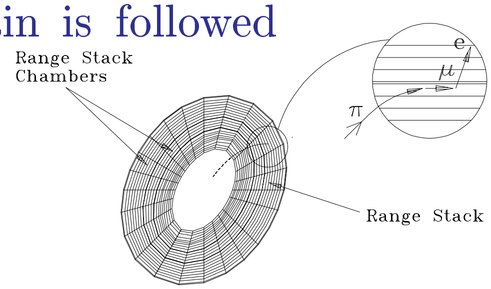


Wait 2ns for decay
Then π^+ tracked & momentum analyzed in UTC (B=1T)

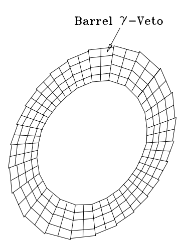


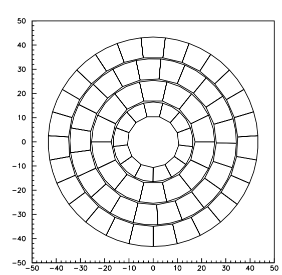


π^+ then ranges out in an Range Stack (scint. + straw ch.)
Range/energy/momentum can be compared.
Also $\pi^+ \to \mu^+ \to e^+$ decay chain is followed



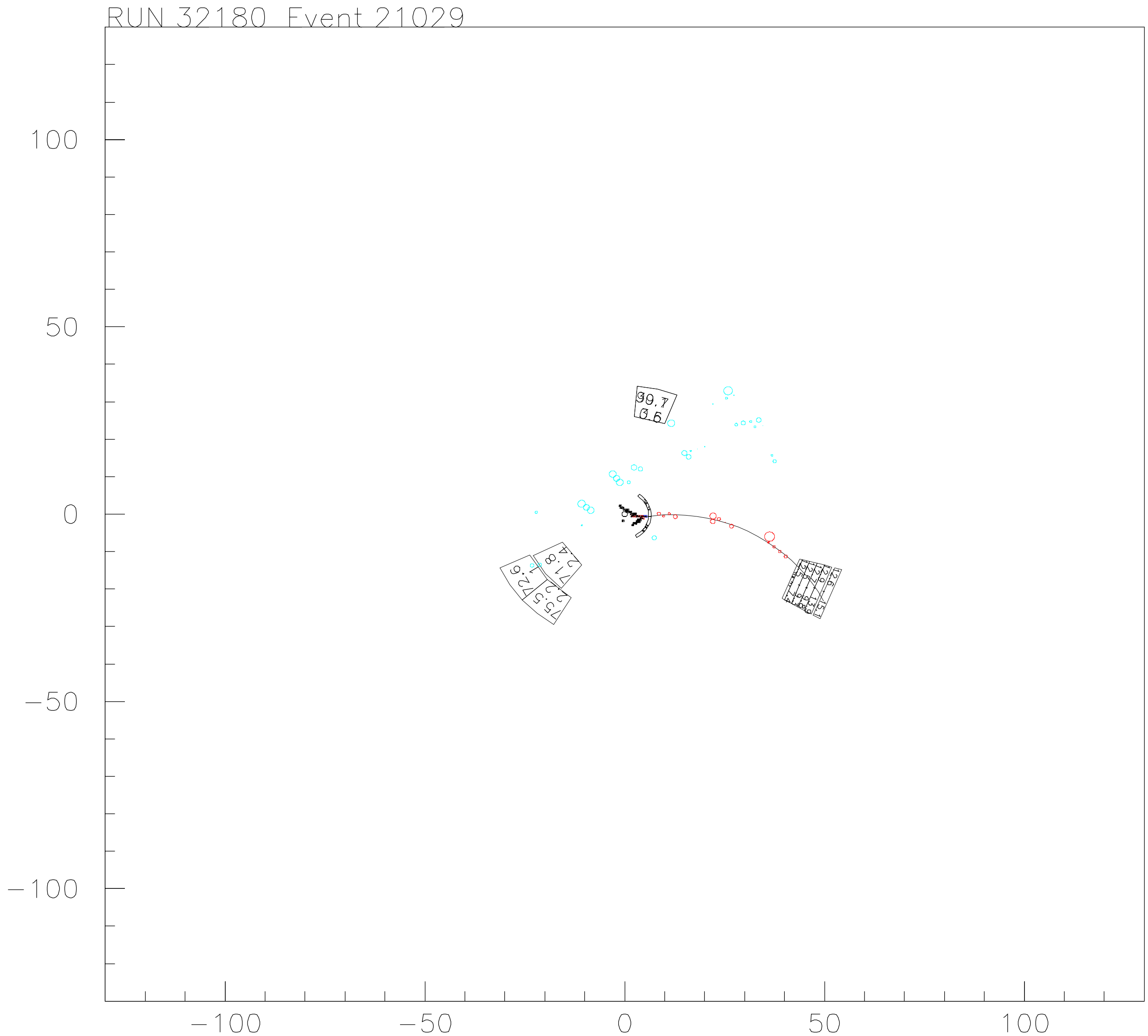
Hermetic photon vetoing via barrel Pb-scint system (BV)
+ CsI-pure endcaps (EC)

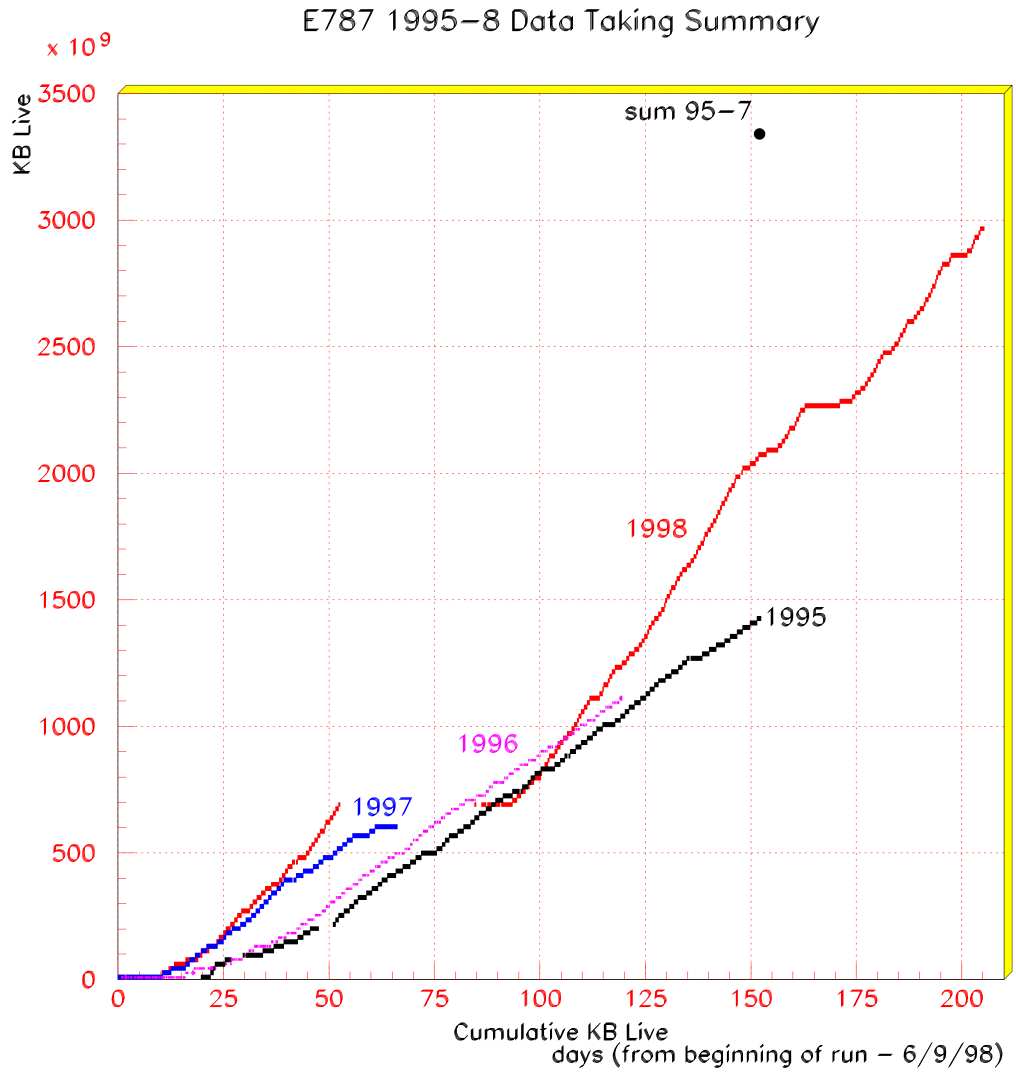




Get $> 10^6 : 1$ π^0 rejection, $> 10^8 : 1$ μ^+ rejection
Also very good kinematic rejection of two-body decays.

CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029





- $B(K^+ \to \pi^+ \nu \bar{\nu})$ in PNN1 region sensitivities
  - '95 : 4.2×10^{-10}
  - '95-'97 : 1.5×10^{-10}
  - '95-'98 : $\sim 0.8 \times 10^{-10}$

- $B(K^+ \to \pi^+ \nu \bar{\nu})$ in PNN2 region sensitivities
  - Only 96 data analysed so far.

    1.12×10^{12} kaons

    $6M$ kaons in 1.6 sec at 730 MeV/c (24% pion cont.)

    Known hardware problem in PBG detector.

PNN2 after pass1

Data reduction cuts ONLINE

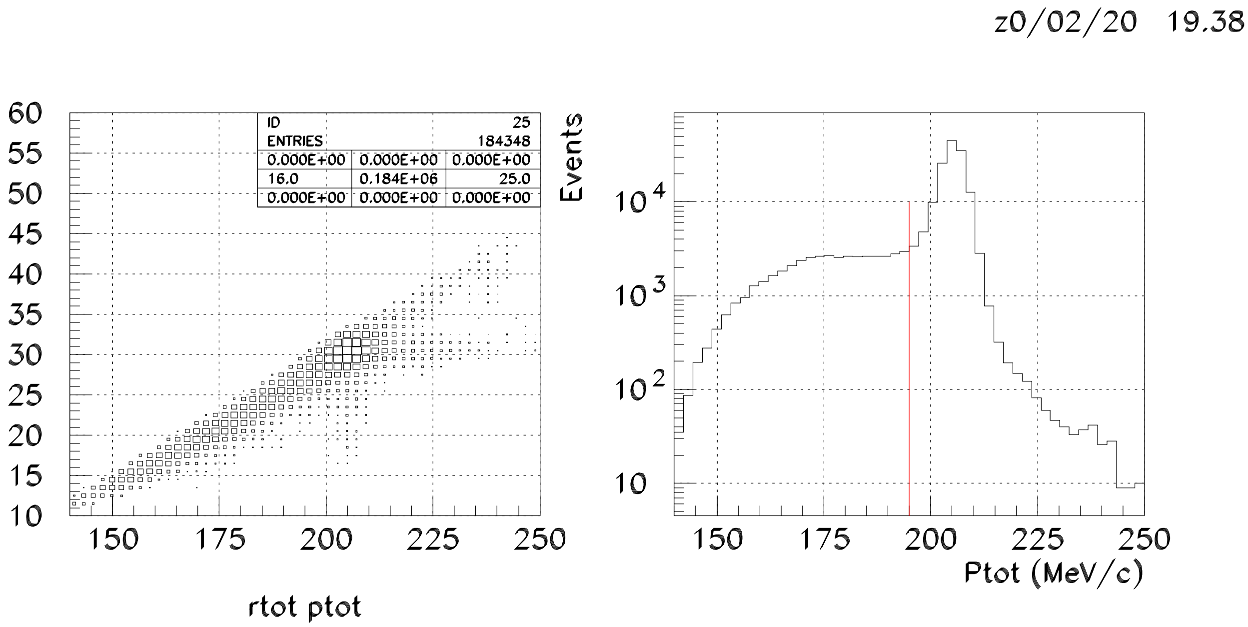
- Require single kaon using Cerenkov.
- Require single charged decay product after 1.5 ns delay.
- Require charged particle to penetrate range stack between layers 6-18.
- Require target and range stack hit pattern consistent with PNN.
- Require $\pi \to \mu$ decay using TD/ASIC system.
- Require no photon hit in Barrel and endcap ($> 20 MeV$).

Data reduction at PASS1

- Reconstruct kaon, pion, photon hits and calcuate range, momentum, energy, and time of all hits.
- Further veto on photons in range stack.
- Reconstruct $\pi \to \mu$ decay with detailed fit to pulse shape and make a cut.

Offline signal and background streams.

- KPI2: Cut on range versus momentum to select pions. Cut on beam instrumentation to eliminate scattered beam-particles.
- Muons: Veto on photons to eliminate KPI2.
- Cut on everything except allow extra particles in target.



KPI2 background stream. Plot on left has logarithmic Z-scale.

Blindness: Define 1/3 and 2/3 streams and block out the signal region.
1/3 for tuning cuts
2/3 for measuring background
Open signal region after defining all cuts.

Signal region

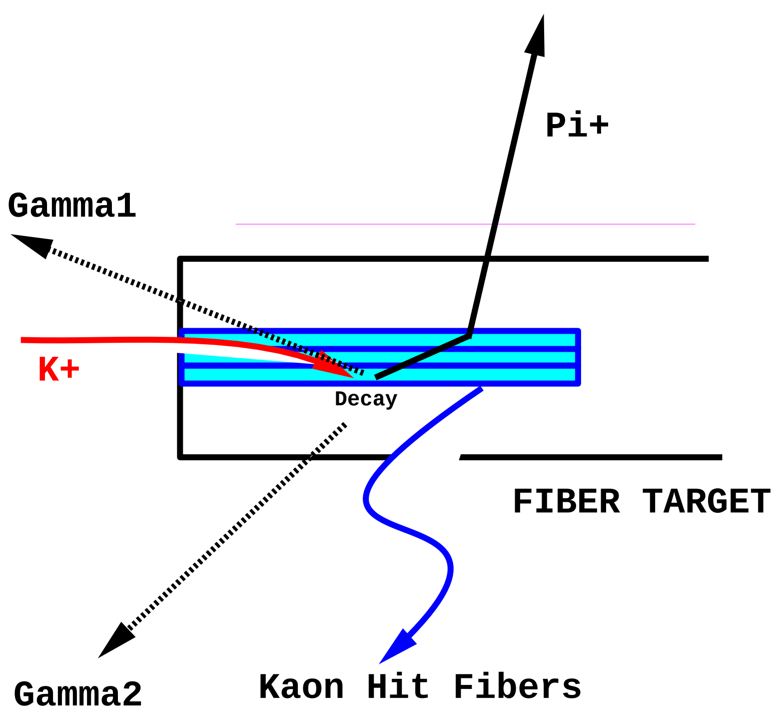
$$140 < PTOT < 195$$

$$12 < RTOT < 27$$

$$60 < ETOT < 95$$

PNN2 data analysis

- Good news: Much larger phase space acceptance below Kpi2 peak.
- Bad news: Huge background from $K^+ \to \pi^+\pi^0$ in which π^+ undergoes interaction in the scintillator fiber target.
- Not possible to simulate all details of the main background. Must be measured from data using two independent cuts and blind analysis techniques.
- After reconstruction of pion and kaon, make fits to all CCD pulses for kaon fibers.
- Find second pulses at pion time overlapping kaon fibers. Cut at 1 MeV threshold.
- Measure rejection of CCD cut by using events tagged by photons.
- Measure Photon veto rejection by using events tagged by CCD second pulses as well as kinks in the track.



PNN2 background picture

- Need to confirm the background model.

  Scanned many samples of events

  Changed selection criteria to study background

  Monte Carlo of $K^+ \to \pi^+\pi^0$ scattering.

- Special problem: Final few events remaining in the background sample may have contamination from $K^+ \to \pi^+\pi^-e^+\nu$ or other reactions.

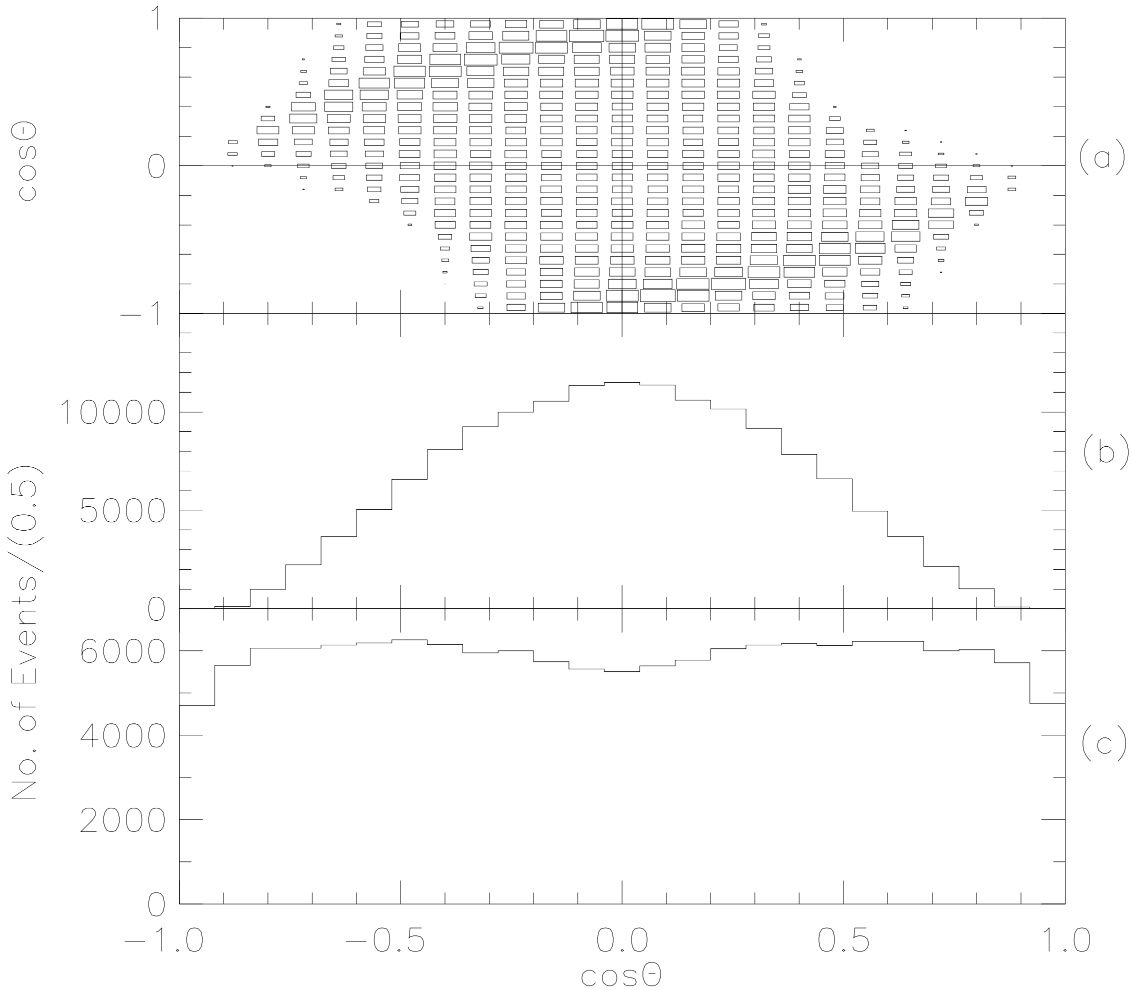
Total photon veto rejection

Type	HEX R_{HEX}	BV-EC-RDP1 R_{BEP}	Offline R_{OFF}	Total $\times 10^5$ R_{PV}
KPI2BOX	2.62 ± 0.04	13000 ± 156	147 ± 21	50.1 ± 7.0
PNN2BOX	1.66 ± 0.15	942 ± 29	241 ± 62	3.77 ± 1.10

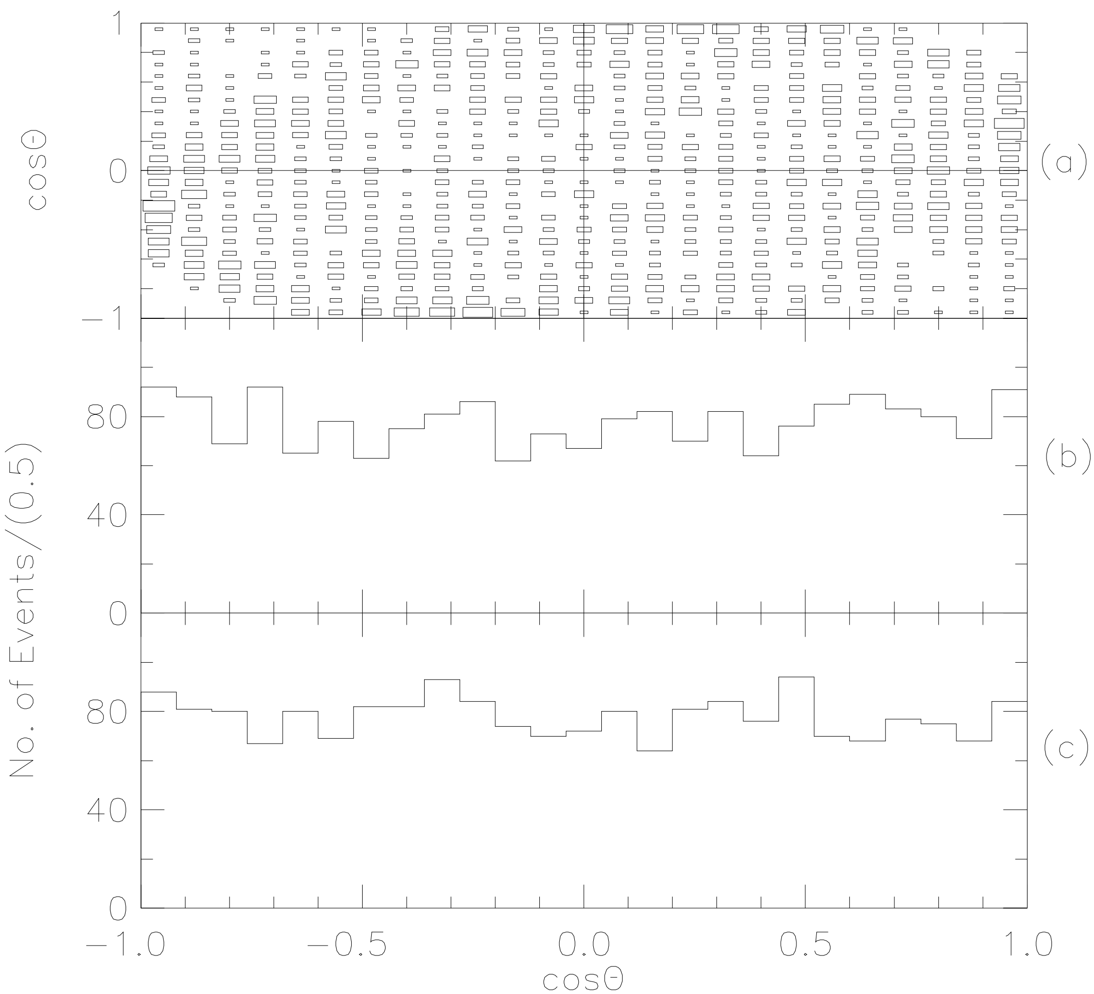
The online and offline photon veto rejections for KPI2 peak and PNN2 box type events.

Important cuts

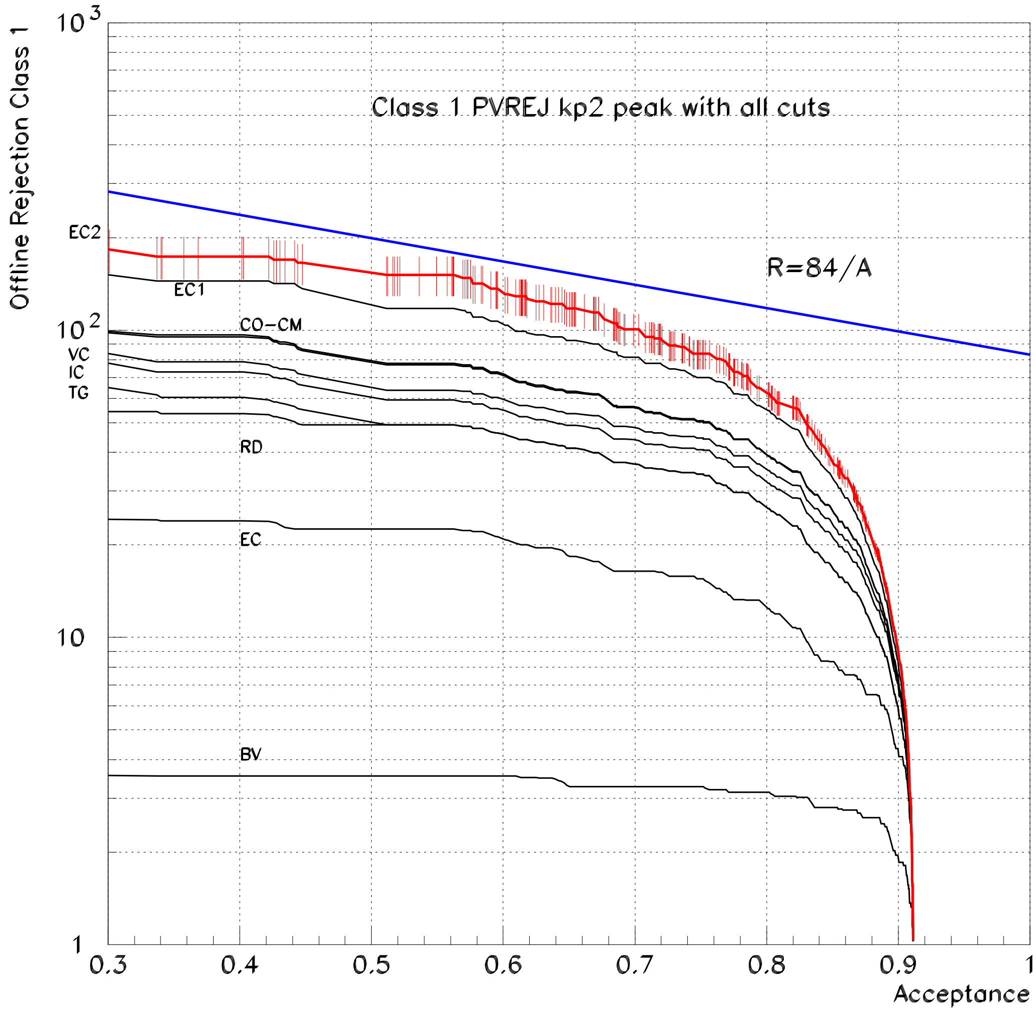
- Charged track kinematics consistent with pion mass.
- Photon veto.
- Track fitting in the fiber-target. No kinks. Pion points back to kaon vertex fiber.
- CCD pion-time energy less than 1 MeV.
- Kaon decay time $> 6ns$.
- No extra particles in the fiber-target.
- No extra particles entering along with the kaon.



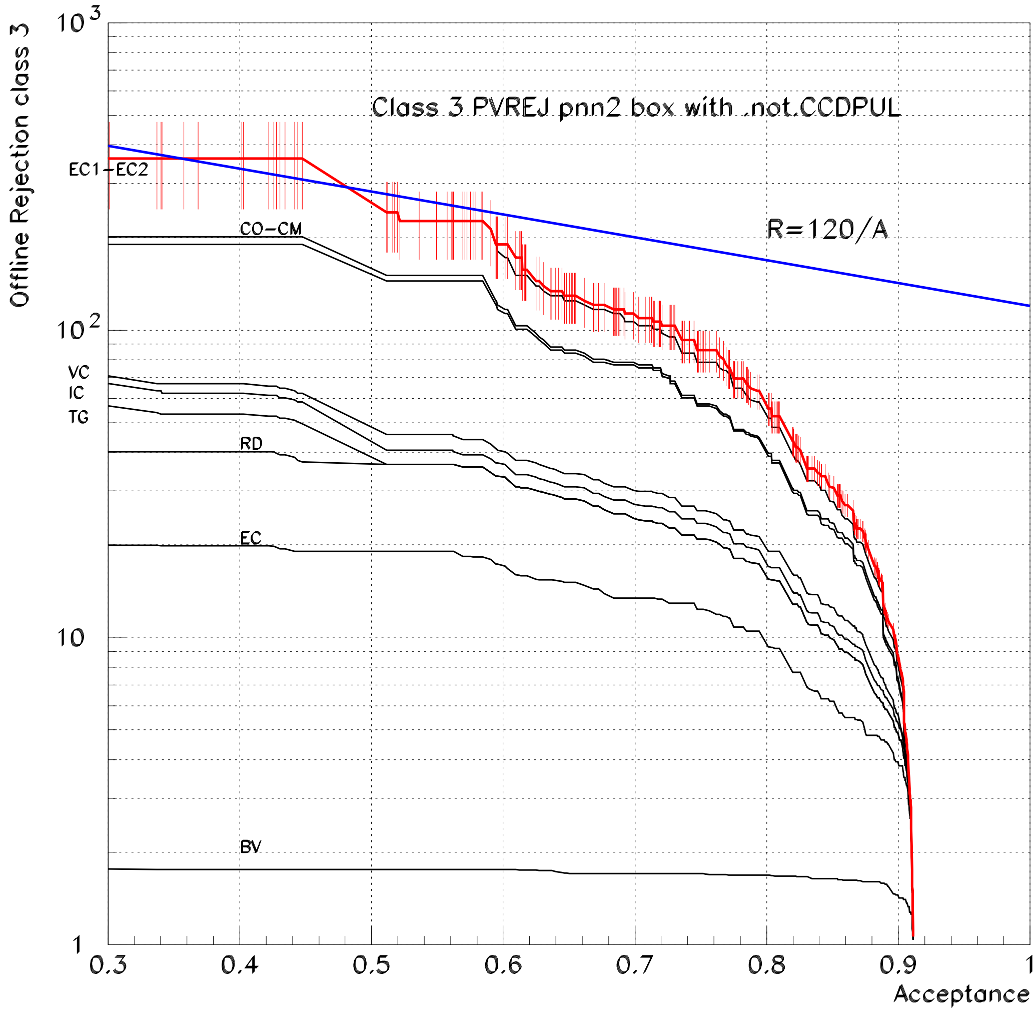
Monte Carlo simulation. θ is the angle of a photon from $K^+ \to \pi^+\pi^0$ decay. Angle of the smaller energy photon versus the larger energy photon is plotted for events in which the π^+ was accepted in the E787 geometry. The π^+ momentum is in the 205 MeV/c peak.



Monte Carlo simulation. θ is the angle of a photon from $K^+ \rightarrow \pi^+\pi^0$ decay. Angle of the smaller energy photon versus the larger energy photon is plotted for events in which the π^+ was accepted in the E787 geometry. The π^+ momentum is below 195 MeV/c because of scattering.



OFFLINE photon veto rejection on KPI2 peak data.



OFFLINE photon veto rejection on data in PNN2 box (below KPI2 peak) that has failed the CCD cut.

Total photon veto rejection

Type	HEX R_{HEX}	BV-EC-RDP1 R_{BEP}	Offline R_{OFF}	Total $\times 10^5$ R_{PV}
KPI2BOX	2.62 ± 0.04	13000 ± 156	147 ± 21	50.1 ± 7.0
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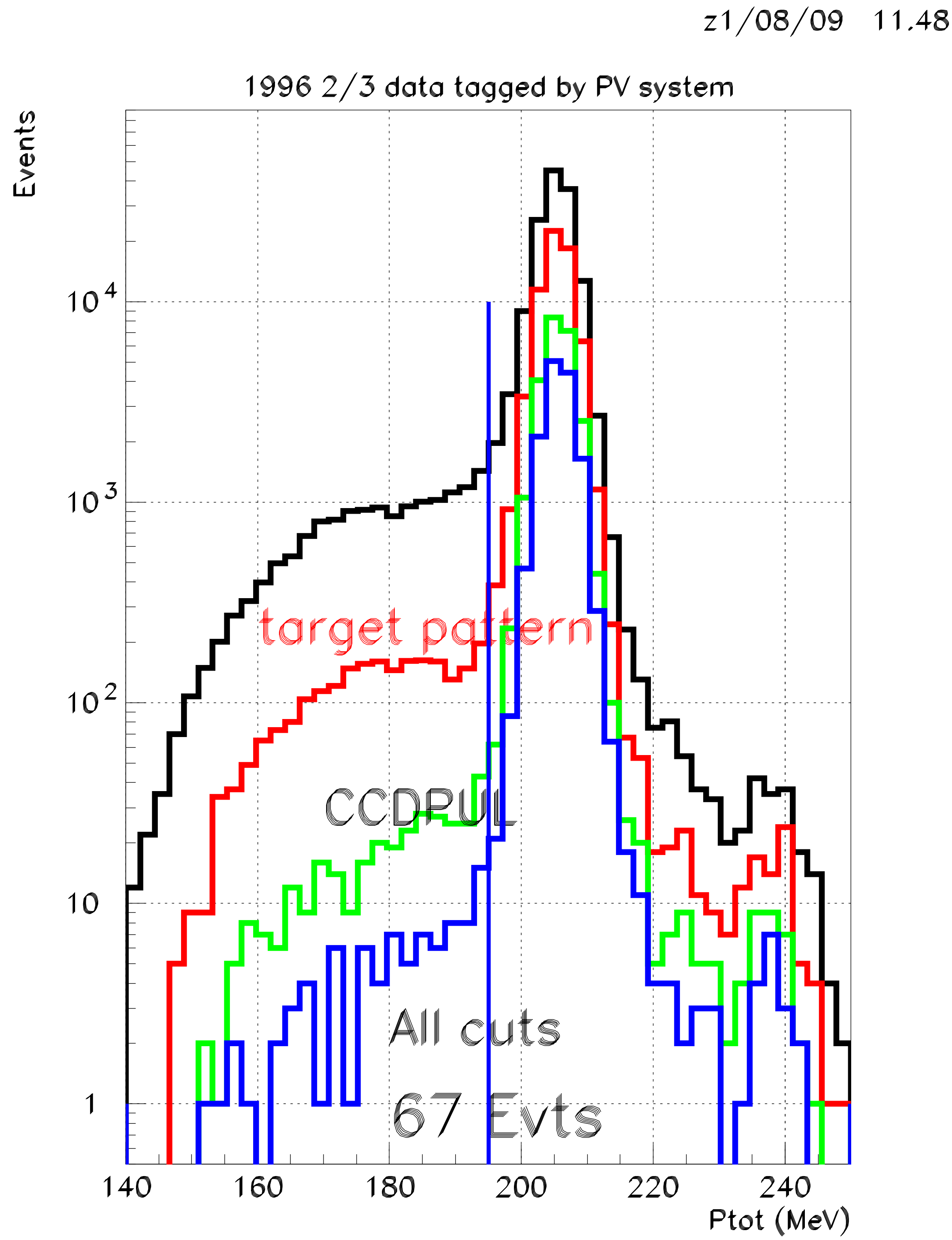
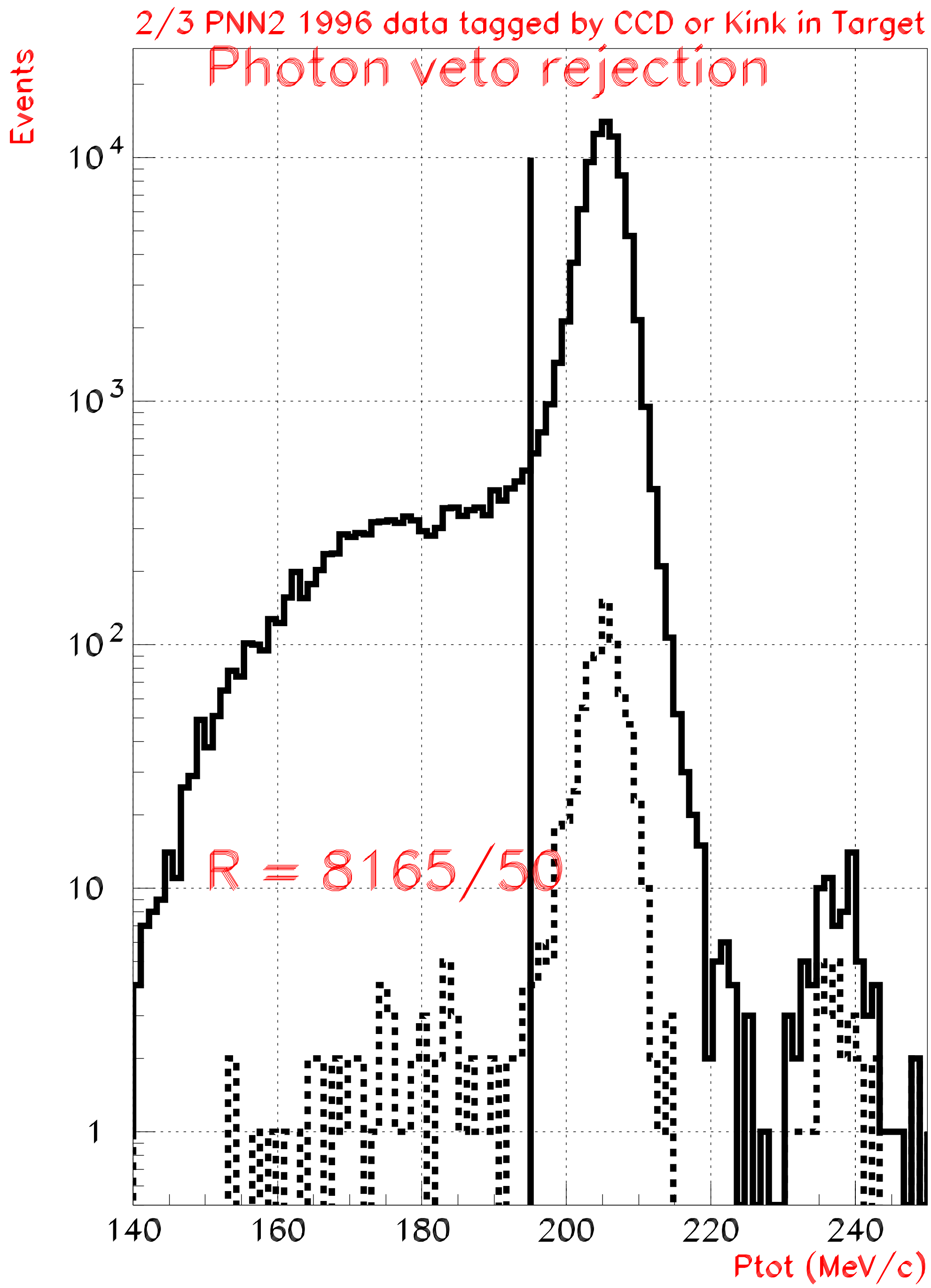
PNN2 Kpi2 background



N = 67



$$\mathbf{Rej}(\overline{\gamma}) = 163 \pm 23$$

$$N_{b.g.} = 1.5 \times N_{Kin.}/R_{\bar{\gamma}} = 0.62$$

PNN2 Final Background Estimate

Table of Backgrounds for PNN2 data

Background	1/3	2/3
KPI2-sct-in-target	0.35 ± 0.12	0.62 ± 0.17
RS-KPI2-sct-in-target	0.004 ± 0.004	0.007 ± 0.006
$K^+ \to \pi^+\pi^0\gamma$	0.021 ± 0.004	0.027 ± 0.004
$K^+ \to \mu^+\nu\gamma$	0.011 ± 0.011	0.007 ± 0.007
1-beam	0.0009 ± 0.0009	0.0003 ± 0.0003
2-beam	0.056 ± 0.056	0.033 ± 0.033
$K^+ \to \pi^+\pi^-e^+\nu$	0.051 ± 0.062	0.026 ± 0.032
Charge Xng	0.011 ± 0.011	0.011 ± 0.011
Total	0.506 ± 0.147	0.731 ± 0.177

Total background estimates from the 1/3 and 2/3 1996 analysis. The background estimate in both columns are for the entire 1996 data set. Explicitly, the 1/3 data set has already bean corrected by factor of 3 and the 2/3 column has been corrected by factor of 1.5.

3 events in the background region just outside the signal. All of them consistent with background estimate.

1 event at 4.2 ns kaon decay time consistent with background estimate of 0.45 ± 0.14 in the 2-6 ns region.

$K^+ \to \pi^+\pi^-e^+\nu$

Key steps in background determination

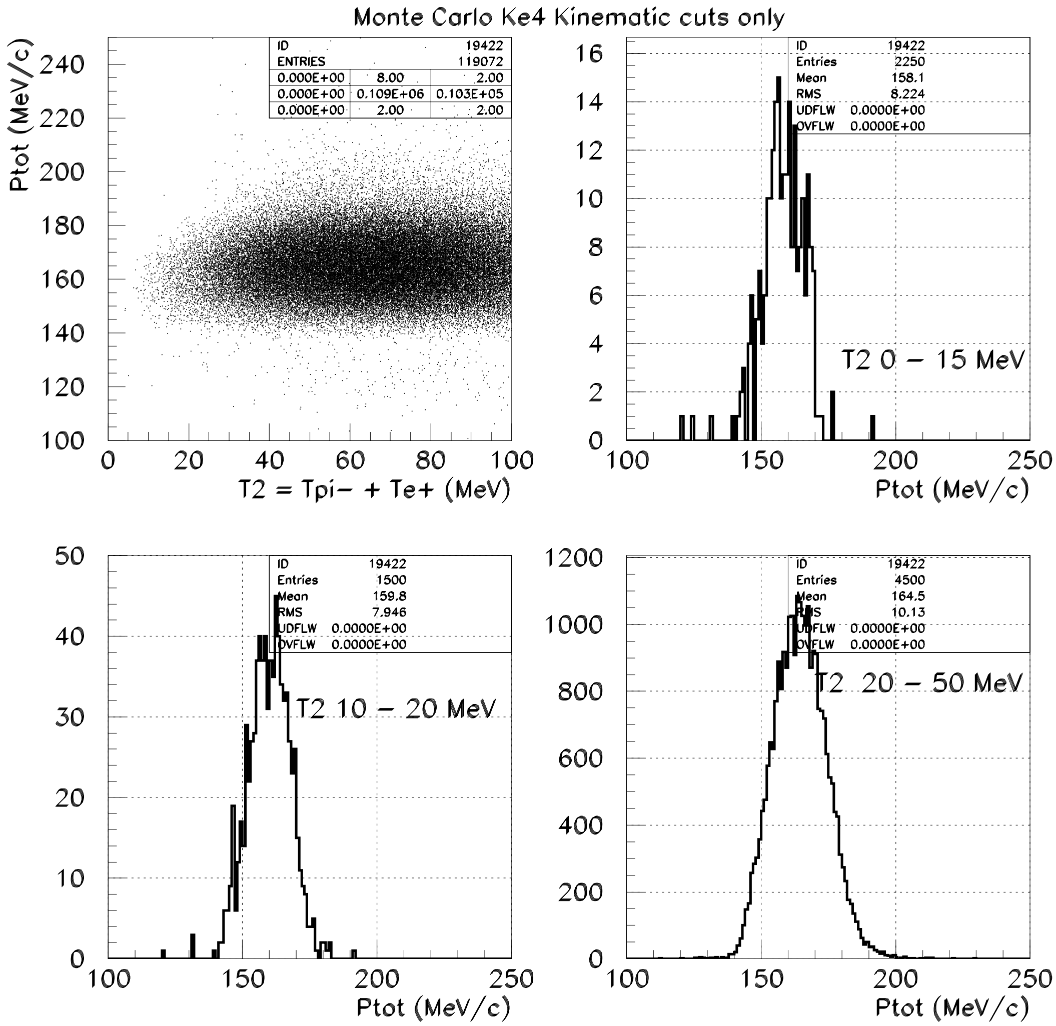
- Branching ratio: 4×10^{-5}.

  No photons.

  π^- can disappear by absorption.

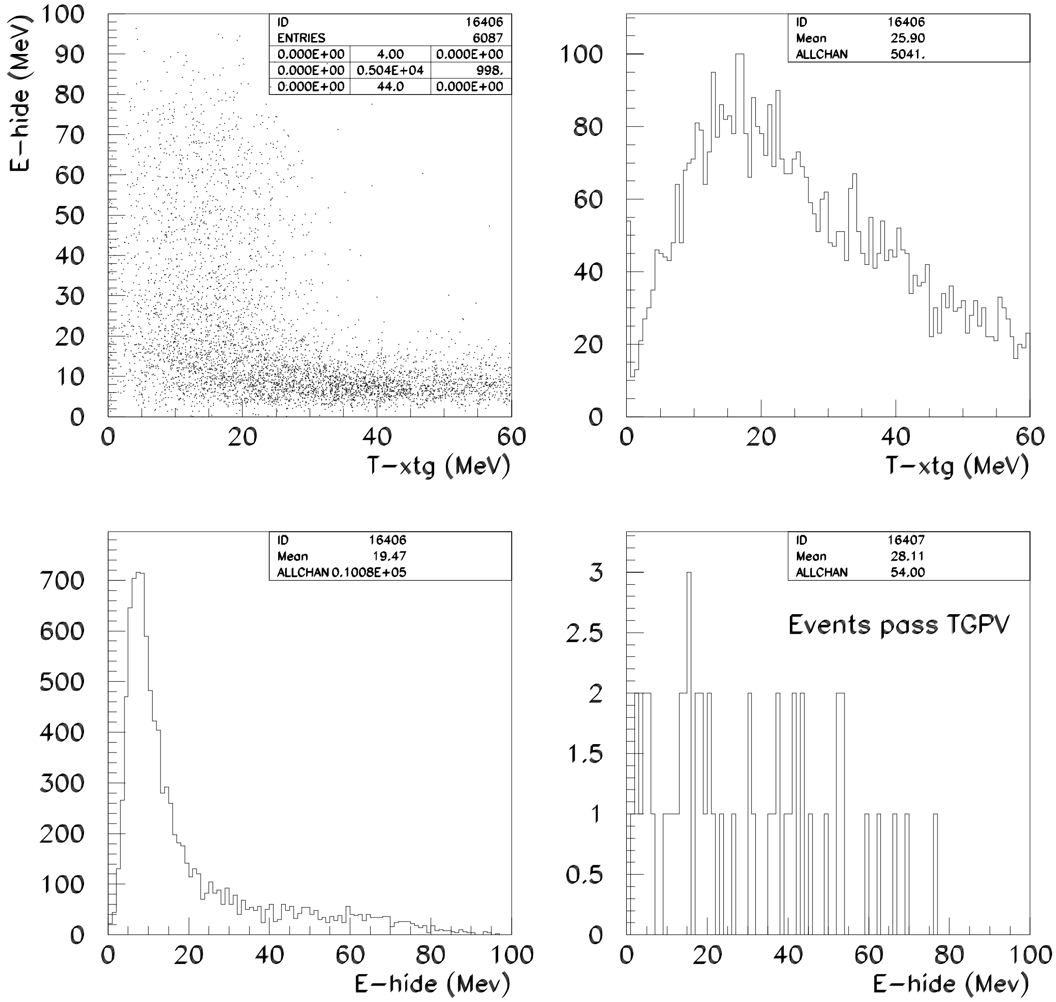
  e^+ can disappear by annihilation.

  π^+ momentum falls in the range of 150 to 190 MeV.
- Identify events in the data.
- Determine effect of CCD cut and target veto cuts.
- Use Monte Carlo and data to estimate background and error.
- Luck factor: no phase space for decay as kinetic energy for π^- and e^+ goes to 0.



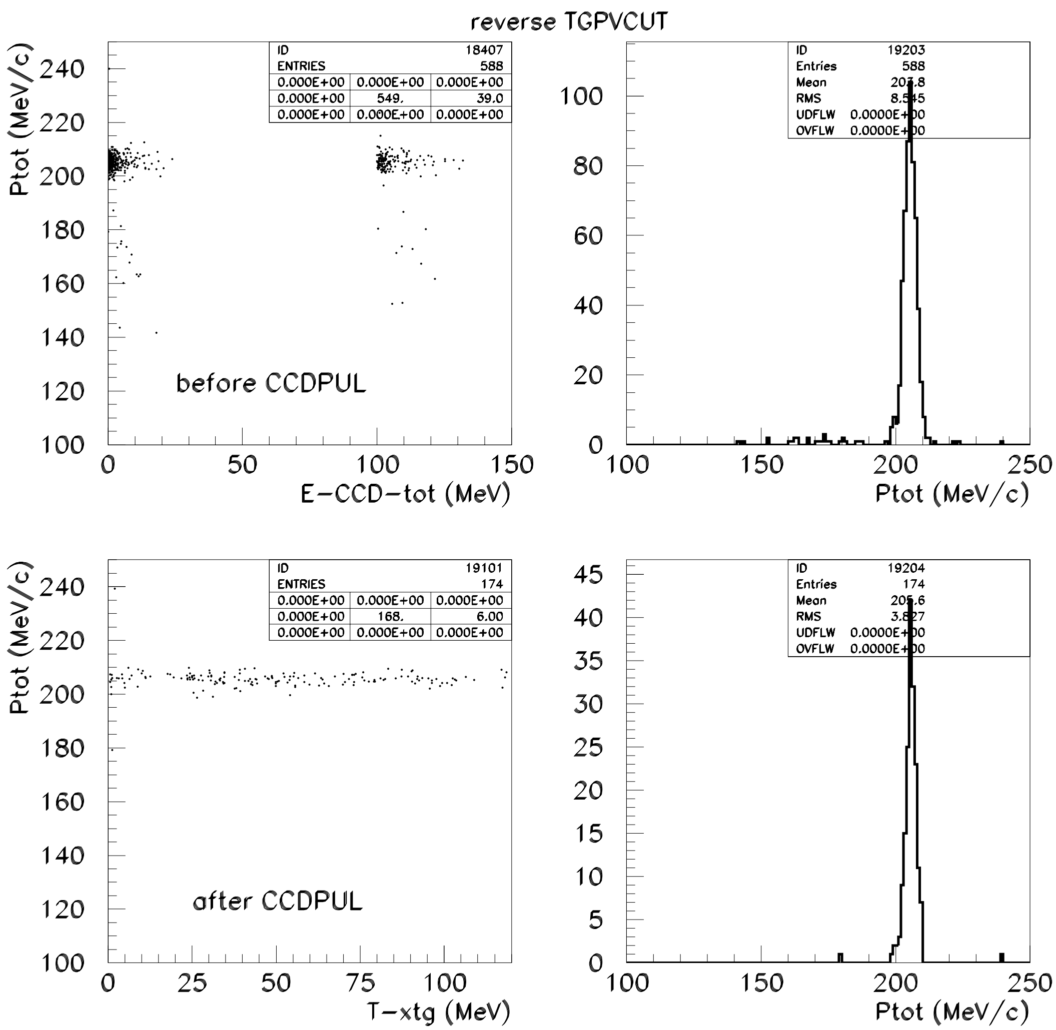
Monte Carlo of $K^+ \to \pi^+\pi^-e^+\nu$. Reconstructed momentum of π^+ versus the kinetic energy of π^- and e^+.

z1/03/26 14.58



Monte Carlo of $K^+ \to \pi^+\pi^-e^+\nu$. This plot with simulation of π^- absorption and e^+ annihilation. $T - xtg$ is the extra energy deposited in the target by π^- or e^+. $E - hide$ is the extra energy at π^+-time hidden under the kaon. In real data it is found by the CCDs.

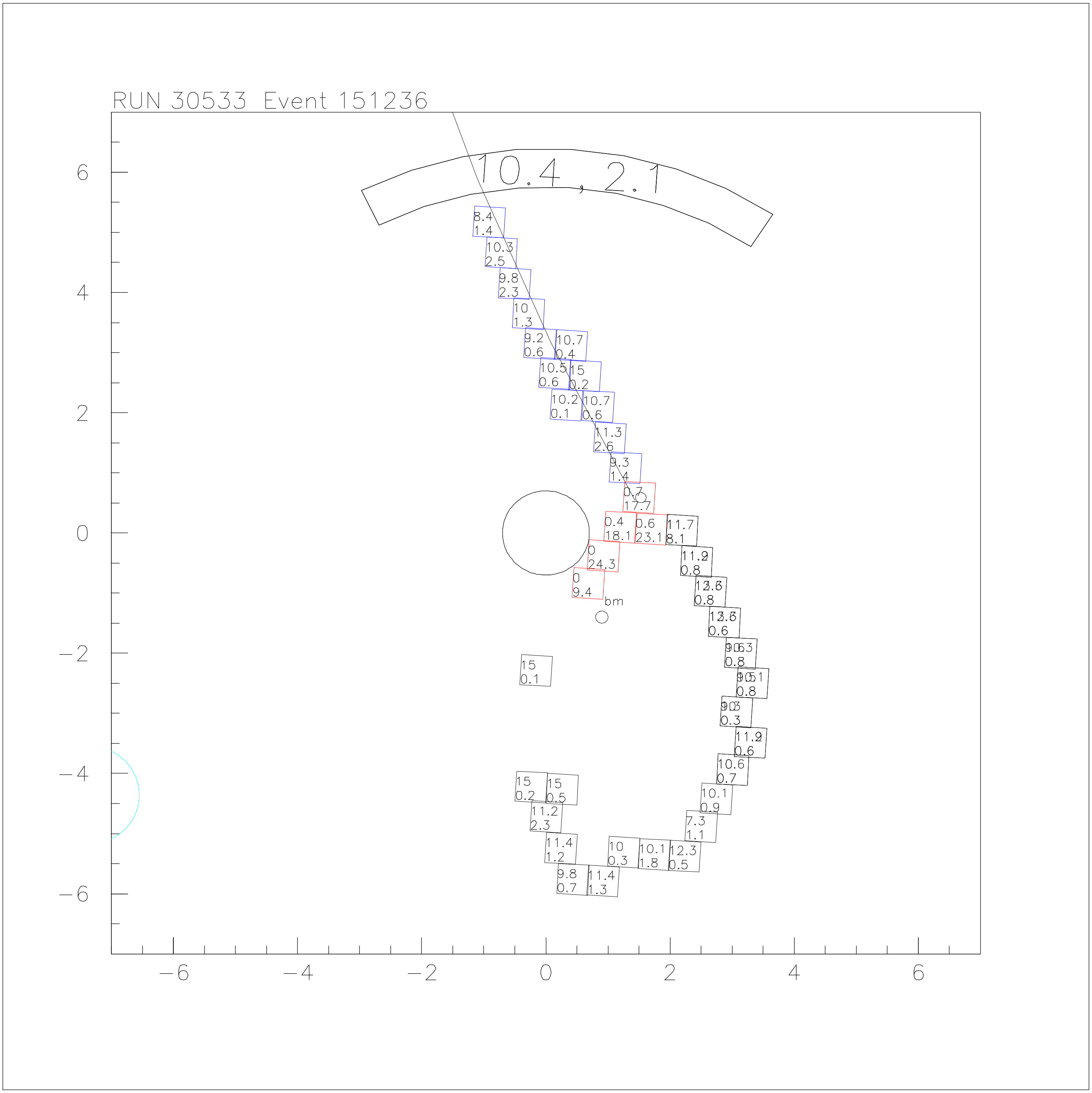
Signal cut is a 1 $MeV \times 1$ MeV box. Based on this plot we estimate the rejection of cutting on $T - xtg$ to be 58 ± 41 for this background.



2/3 ke4 background stream data. With $T - xtg > 1MeV$. 31 events fail both $T - xtg$ and CCD cut. 1 Event left after all cuts.

Background estimate: $1.5 \times \frac{1.0}{58 \pm 41}$

Estimate double checked with other methods. Background small so does not contaminate other estimates !


RUN 30533 Event 151236
10.4 , 2.1
bm

PNN2 Final Background Estimate

Table of Backgrounds for PNN2 data

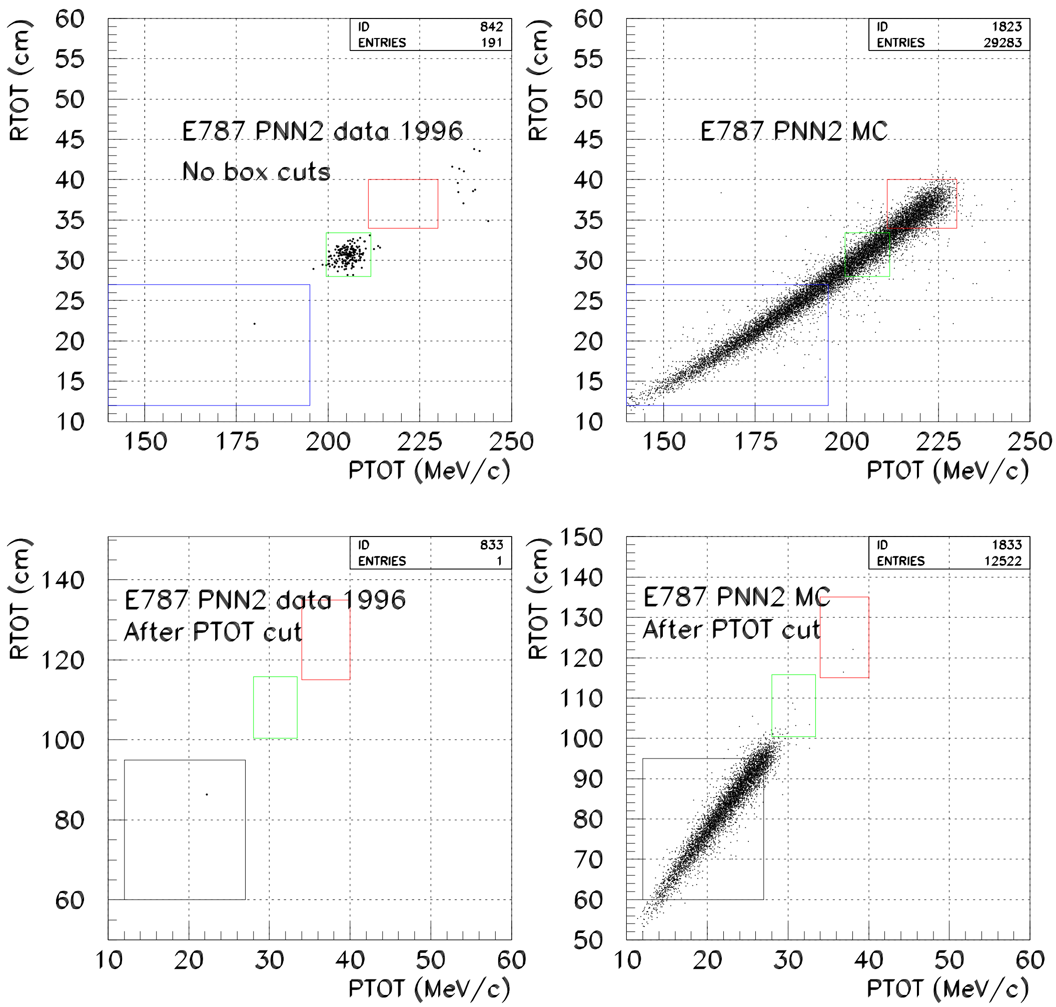
Background	1/3	2/3
KPI2-sct-in-target	0.35 ± 0.12	0.62 ± 0.17
RS-KPI2-sct-in-target	0.004 ± 0.004	0.007 ± 0.006
$K^+ \to \pi^+\pi^0\gamma$	0.021 ± 0.004	0.027 ± 0.004
$K^+ \to \mu^+\nu\gamma$	0.011 ± 0.011	0.007 ± 0.007
1-beam	0.0009 ± 0.0009	0.0003 ± 0.0003
2-beam	0.056 ± 0.056	0.033 ± 0.033
$K^+ \to \pi^+\pi^-e^+\nu$	0.051 ± 0.062	0.026 ± 0.032
Charge Xng	0.011 ± 0.011	0.011 ± 0.011
Total	0.506 ± 0.147	0.731 ± 0.177

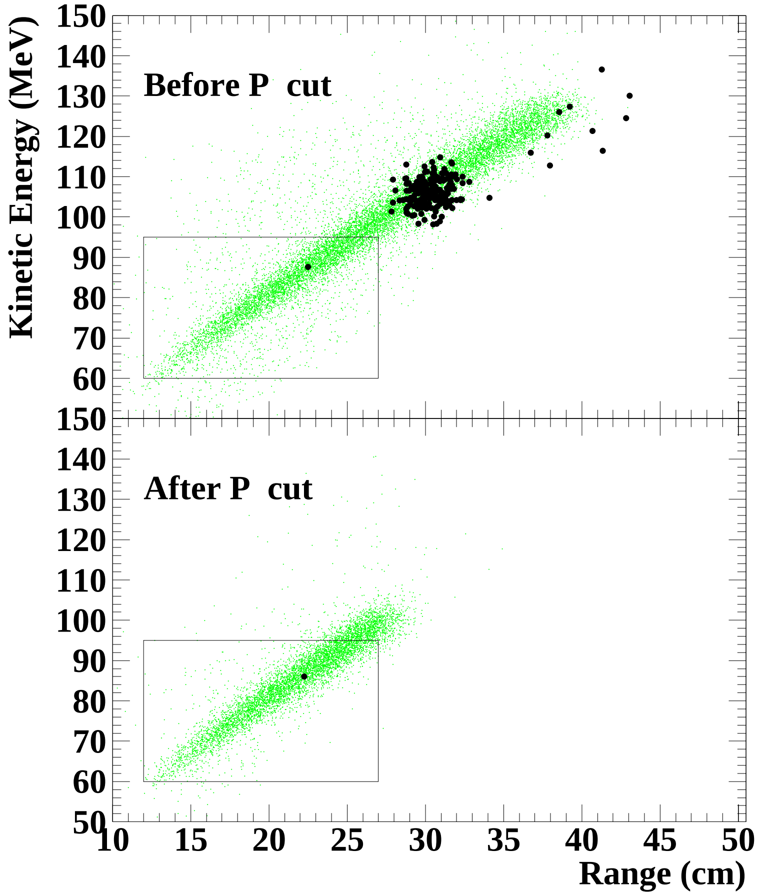
Total background estimates from the 1/3 and 2/3 1996 analysis. The background estimate in both columns are for the entire 1996 data set. Explicitly, the 1/3 data set has already bean corrected by factor of 3 and the 2/3 column has been corrected by factor of 1.5.

3 events in the background region just outside the signal. All of them consistent with background estimate.

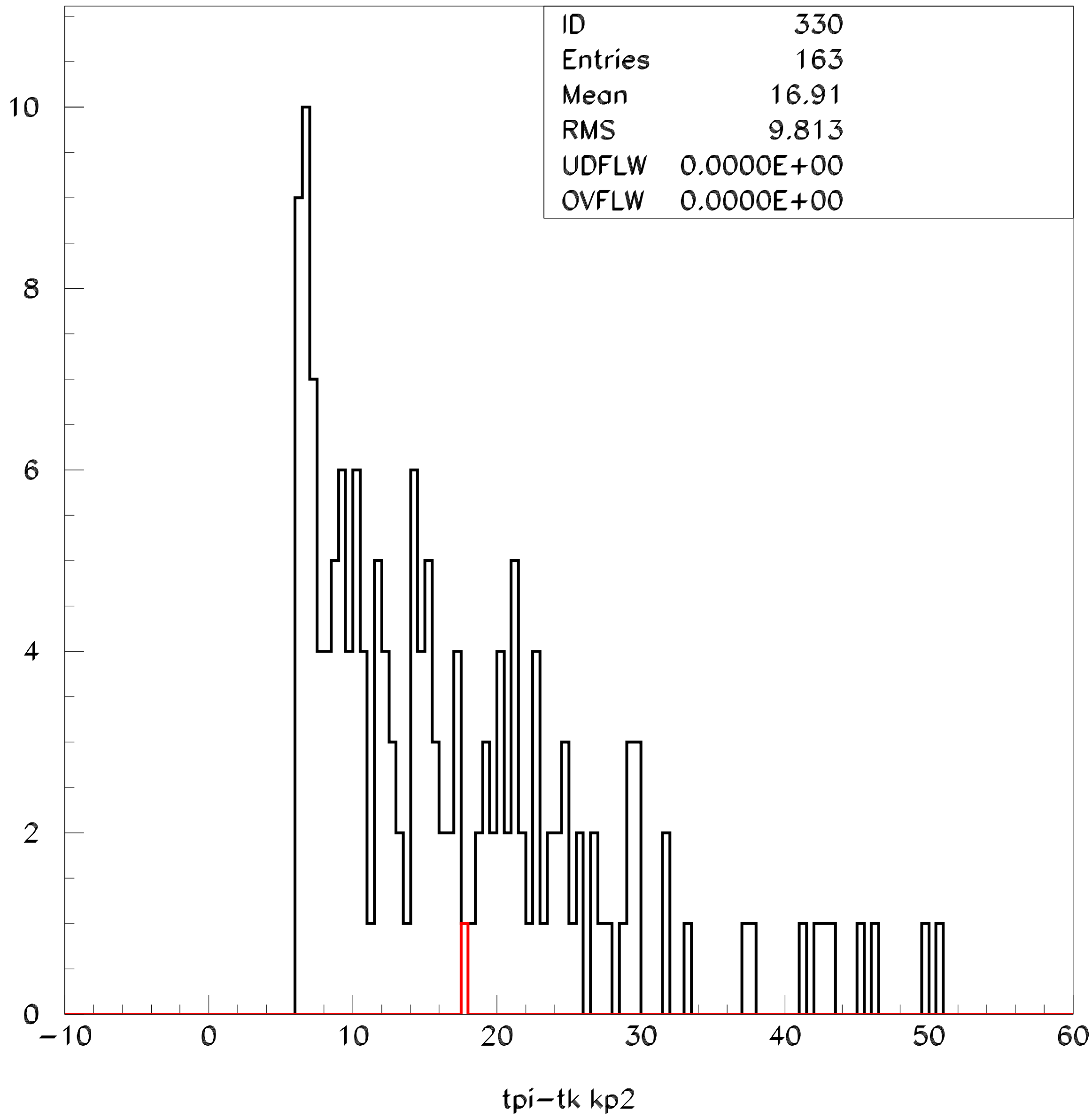
1 event at 4.2 ns kaon decay time consistent with background estimate of 0.45 ± 0.14 in the 2-6 ns region.

Distribution in Signal box

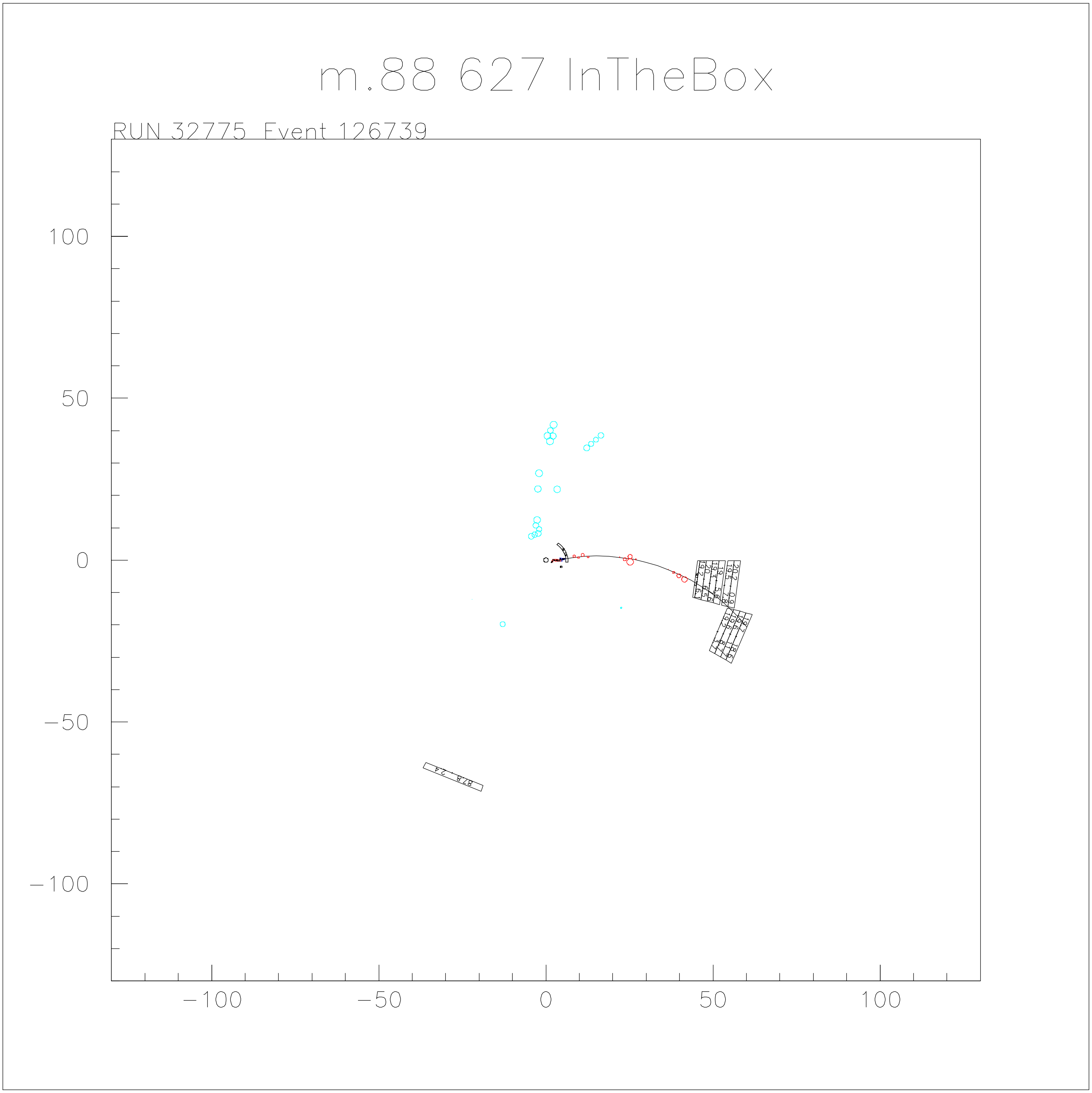


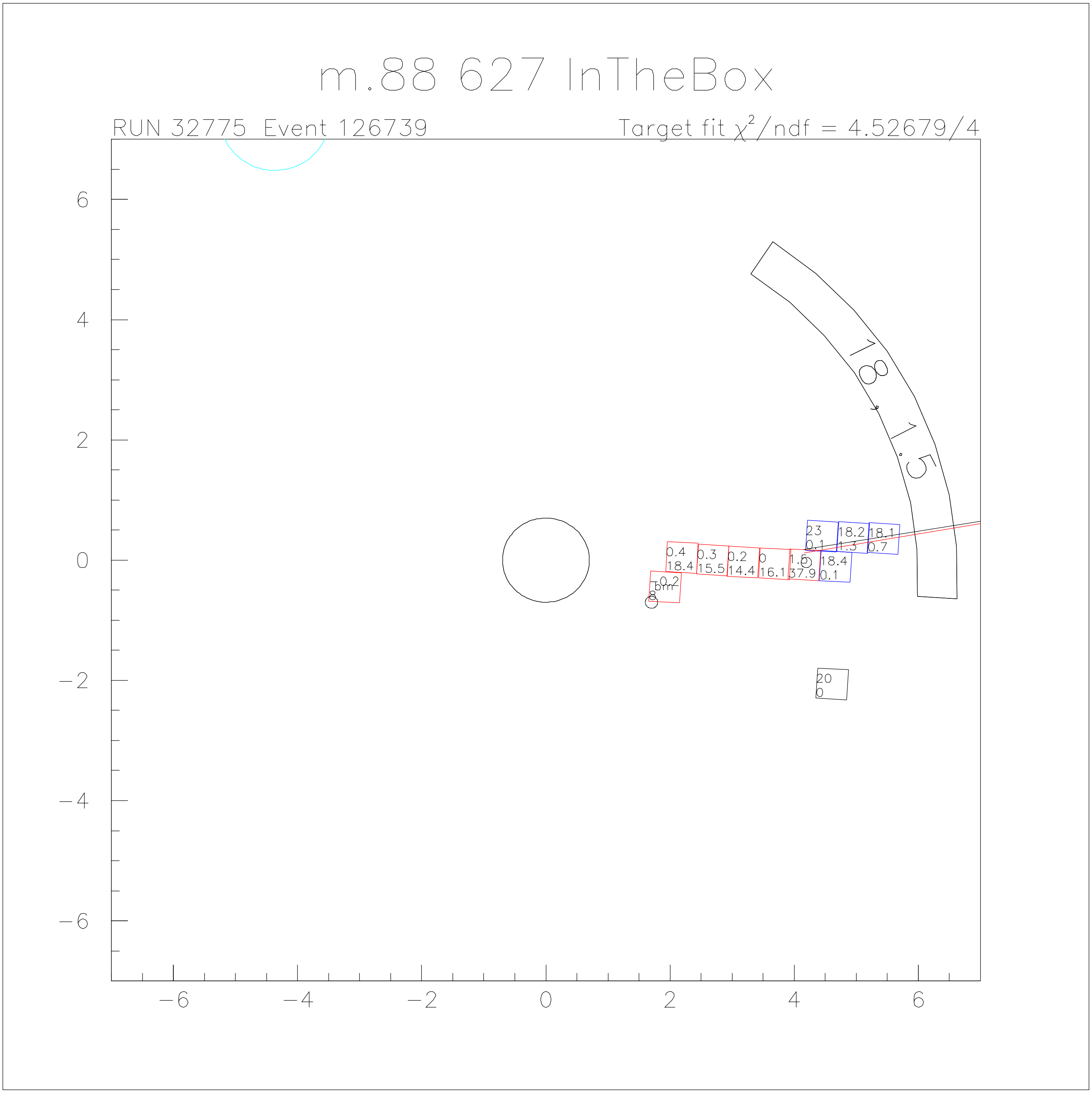


Kinetic Energy (MeV)
Before P cut
After P cut
Range (cm)
150
140
130
120
110
100
90
80
70
60
50
10
15
20
25
30
35
40
45
50

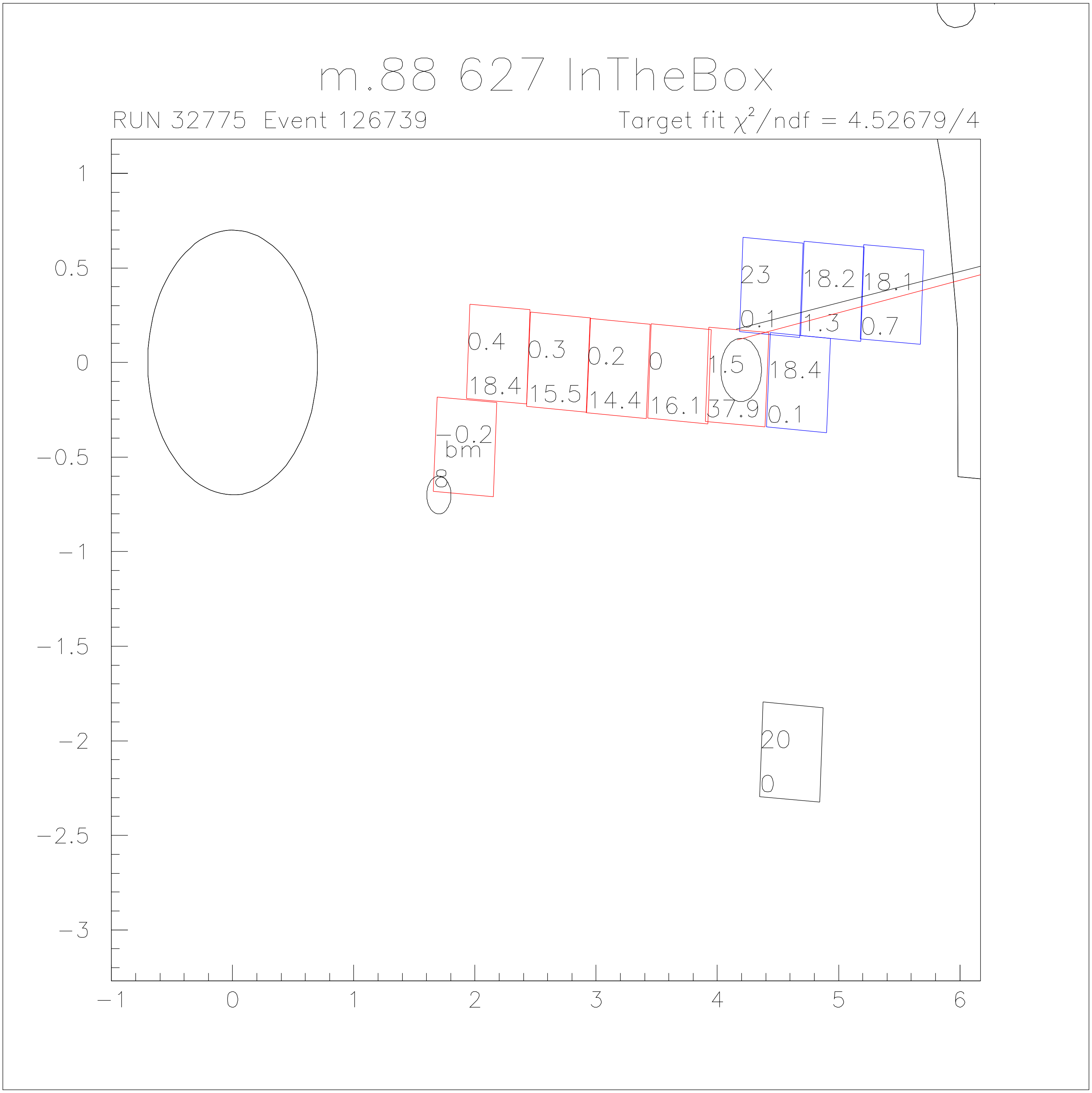


ID 330
Entries 163
Mean 16.91
RMS 9.813
UDFLW 0.0000E+00
OVFLW 0.0000E+00
0
2
4
6
8
10
−10
0
10
20
30
40
50
60
tpi−tk kp2

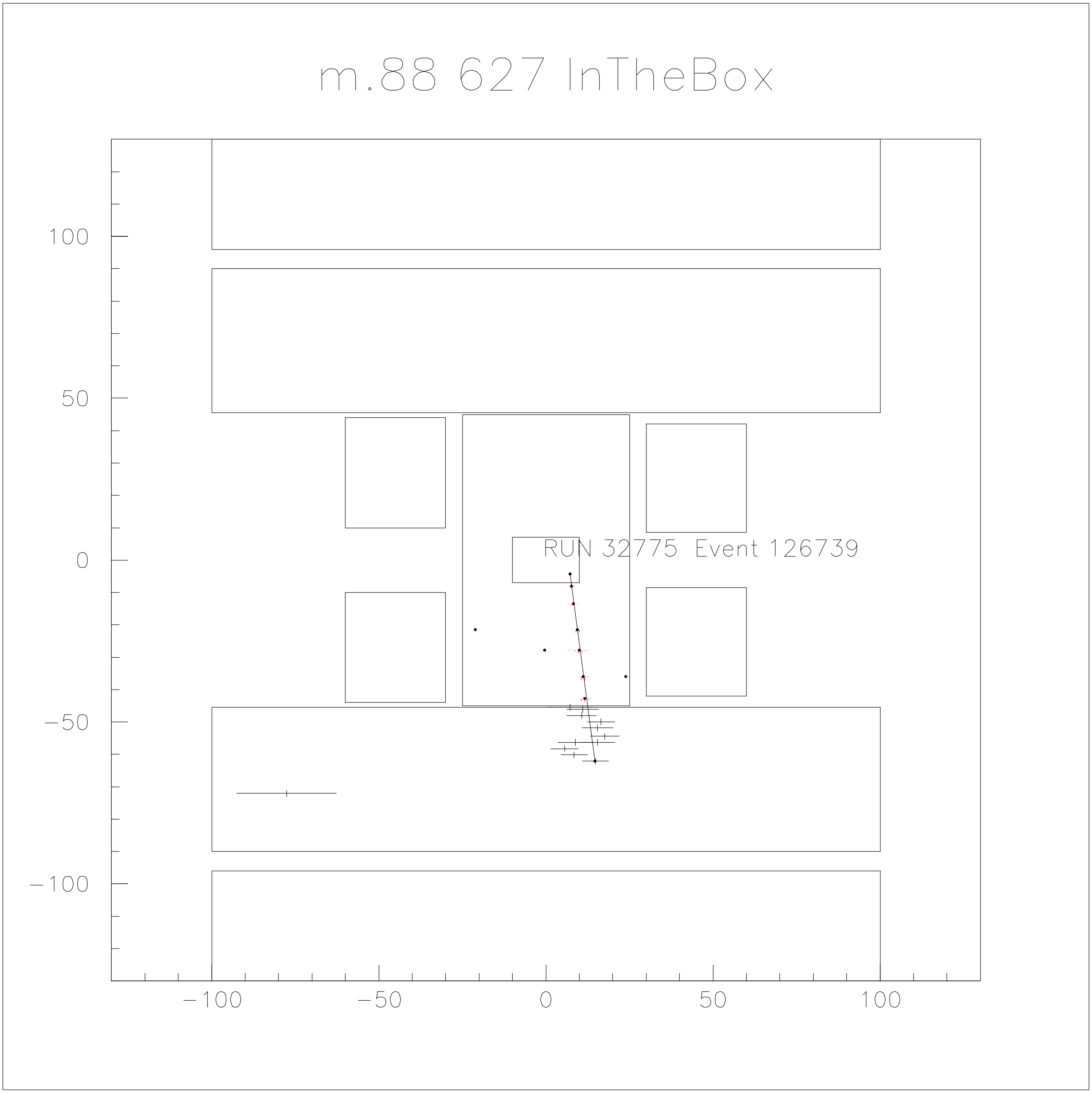

m.88 627 InTheBox
RUN 32775 Event 126739
100
50
0
−50
−100
−100
−50
0
50
100



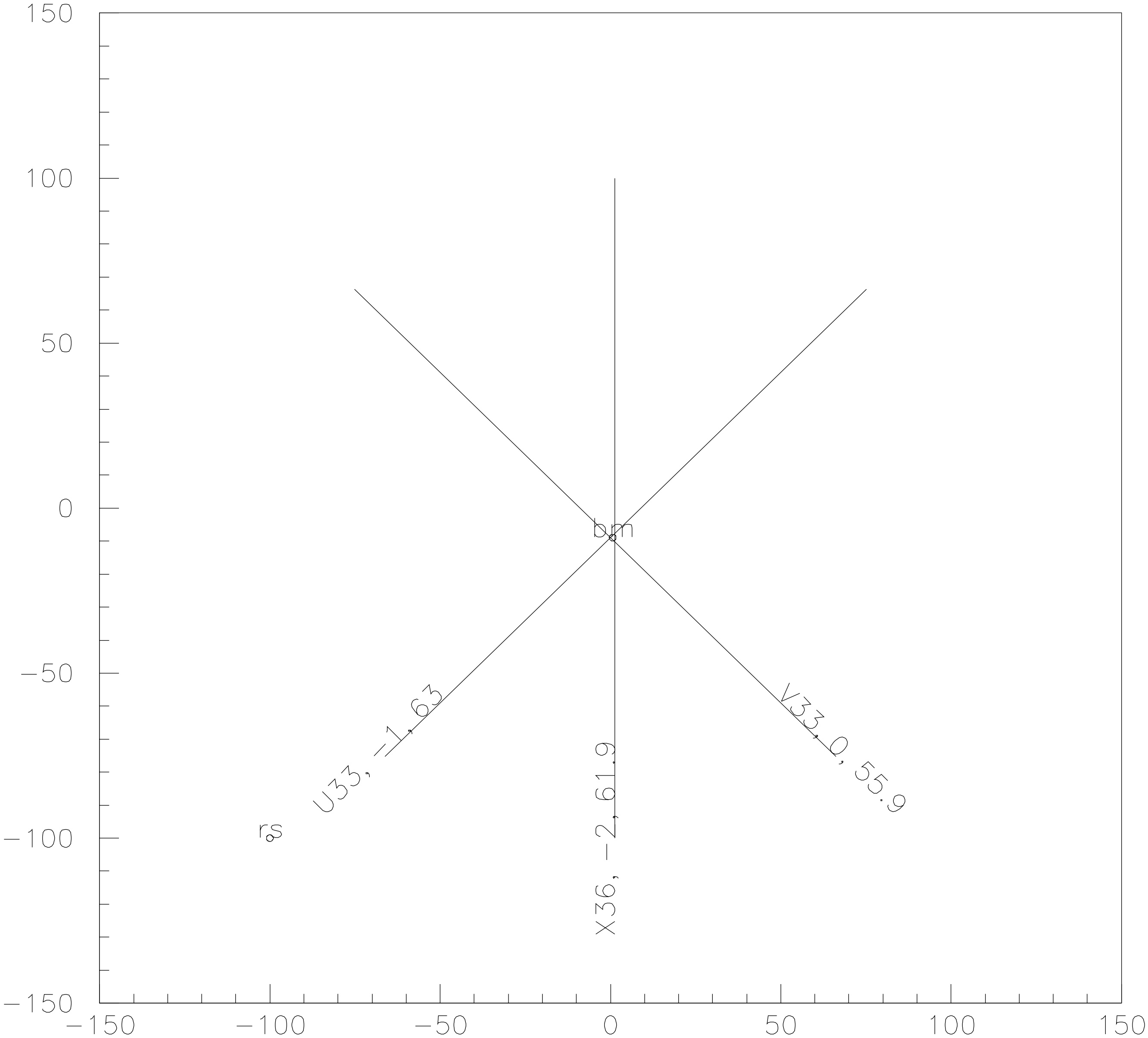
m.88 627 InTheBox
RUN 32775 Event 126739
Target fit χ^2/ndf = 4.52679/4
18.1.5
0.4
18.4
0.3
15.5
0.2
14.4
0
16.1
1.5
37.9
23
0.1
18.2
1.3
18.1
0.7
18.4
0.1
0.2
20
0

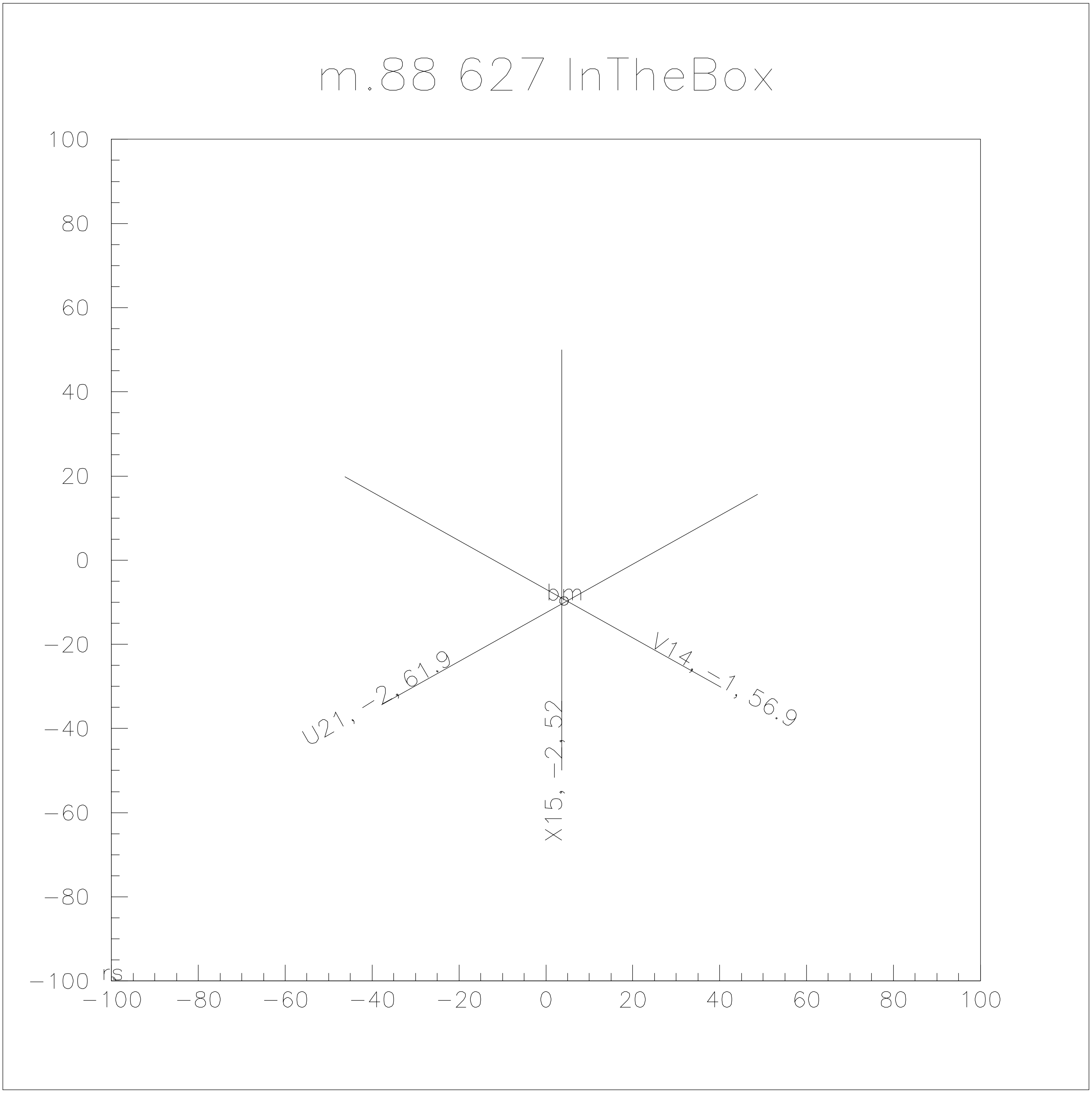


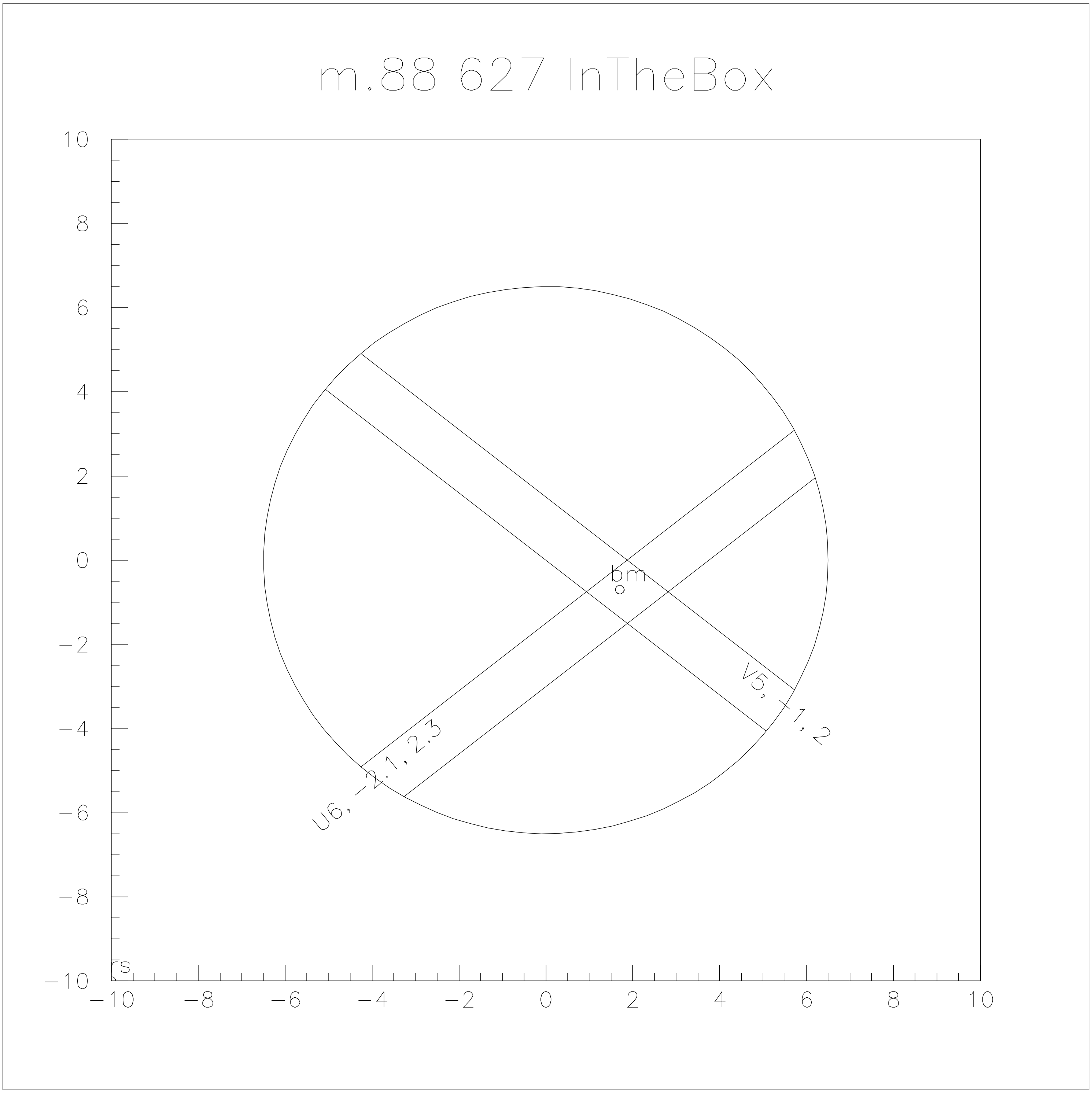
m.88 627 InTheBox
RUN 32775 Event 126739
Target fit χ^2/ndf = 4.52679/4
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
−1
0
1
2
3
4
5
6
23
0.1
18.2
1.3
18.1
0.7
0.4
18.4
0.3
15.5
0.2
14.4
0
16.1
1.5
37.9
18.4
0.1
−0.2
bm
8
20
0


m.88 627 InTheBox
RUN 32775 Event 126739
100
50
0
−50
−100
−100
−50
0
50
100

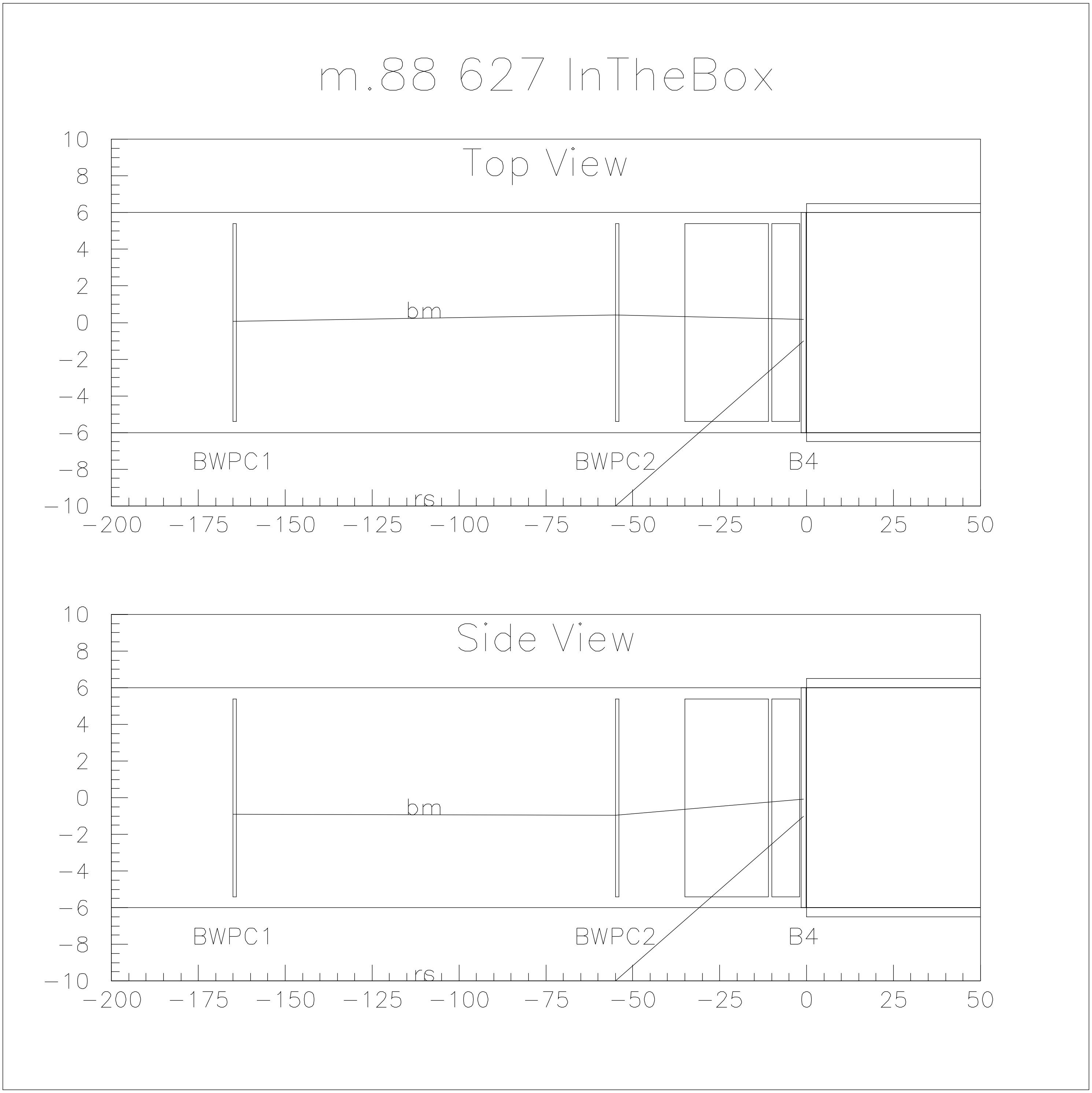
m.88 627 InTheBox

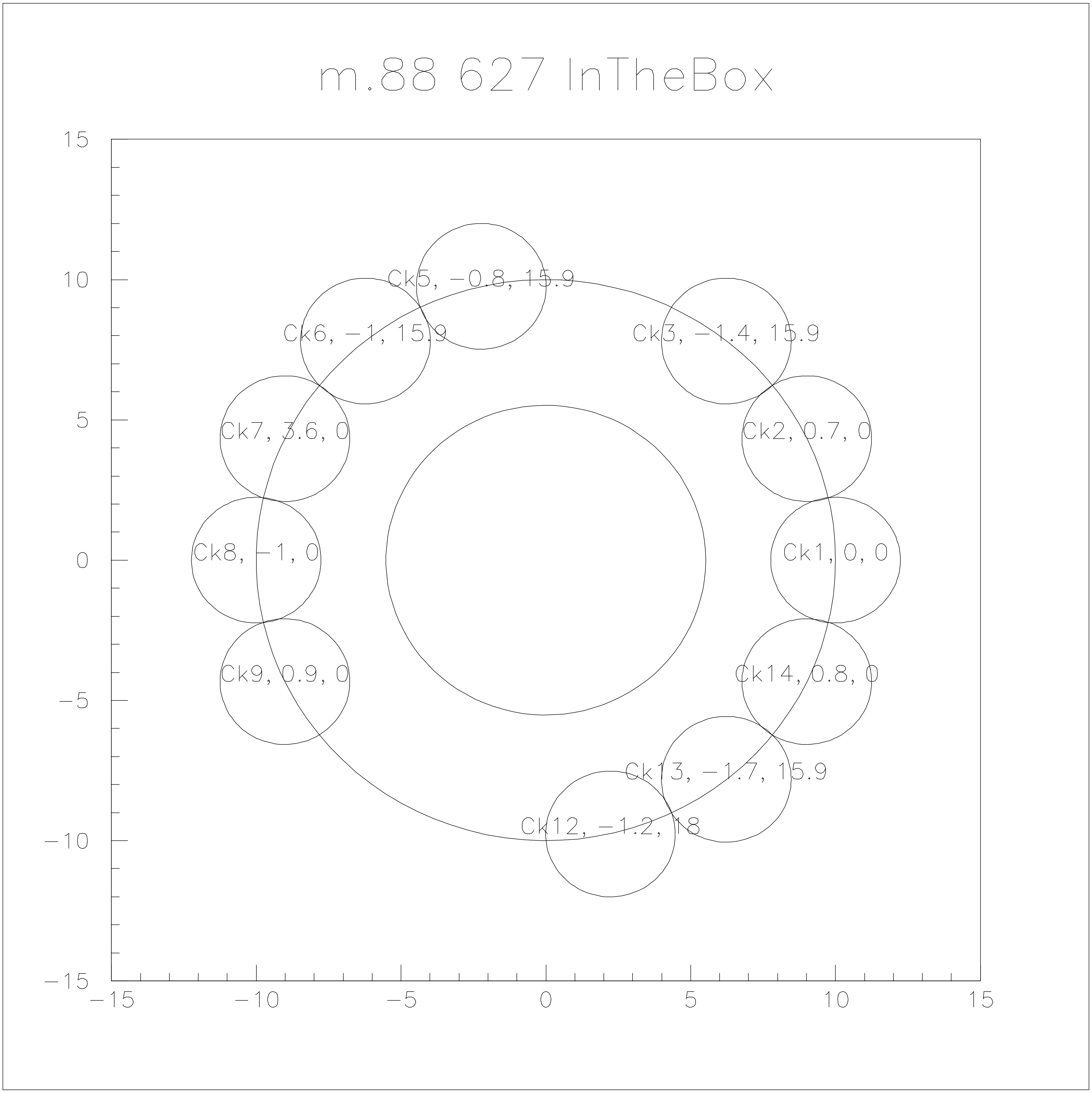


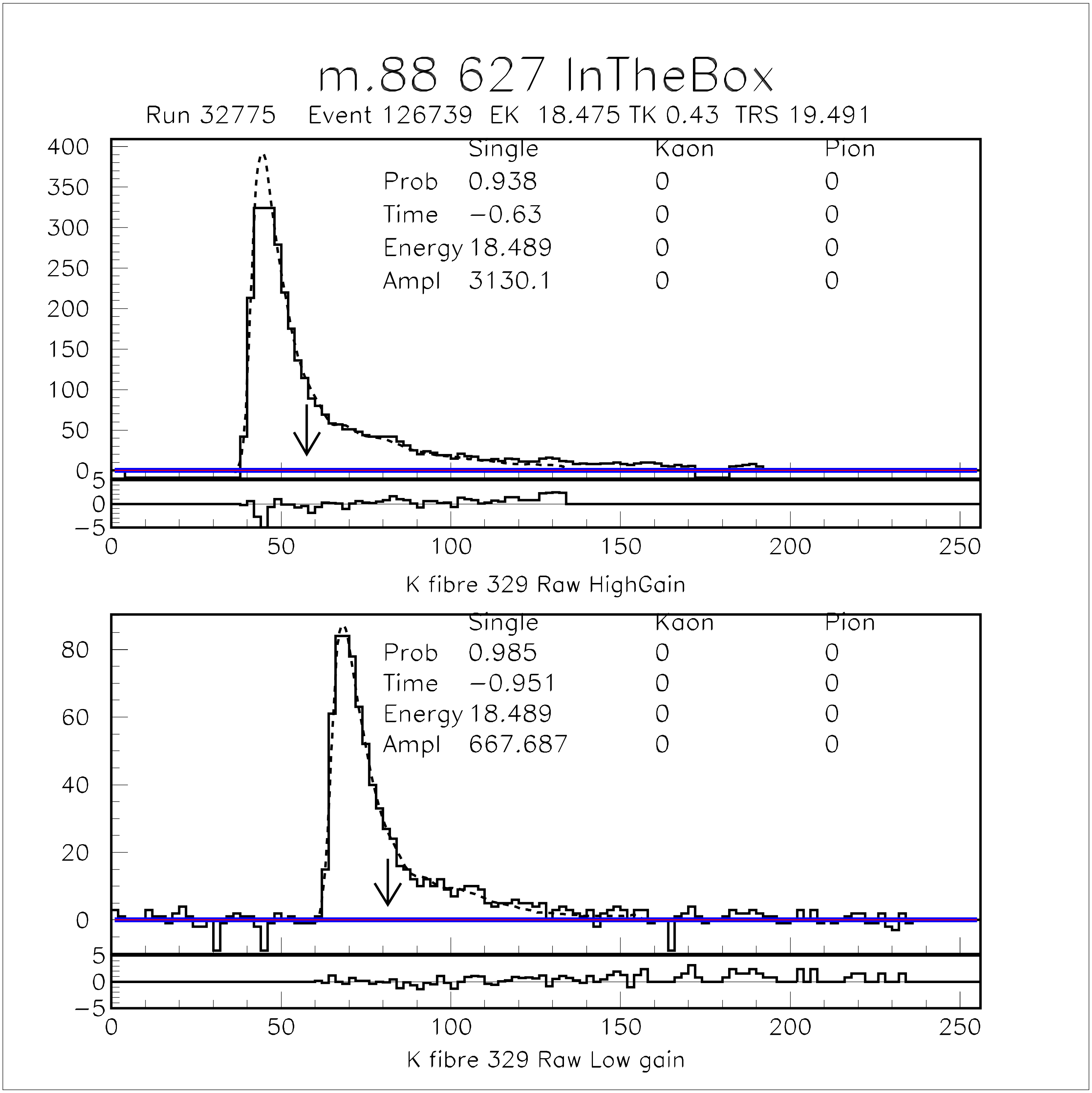

m.88 627 InTheBox
100
80
60
40
20
0
−20
−40
−60
−80
−100
−100
−80
−60
−40
−20
0
20
40
60
80
100
rs
bm
U21, −2, 61.9
X15, −2, 52
V14, −1, 56.9



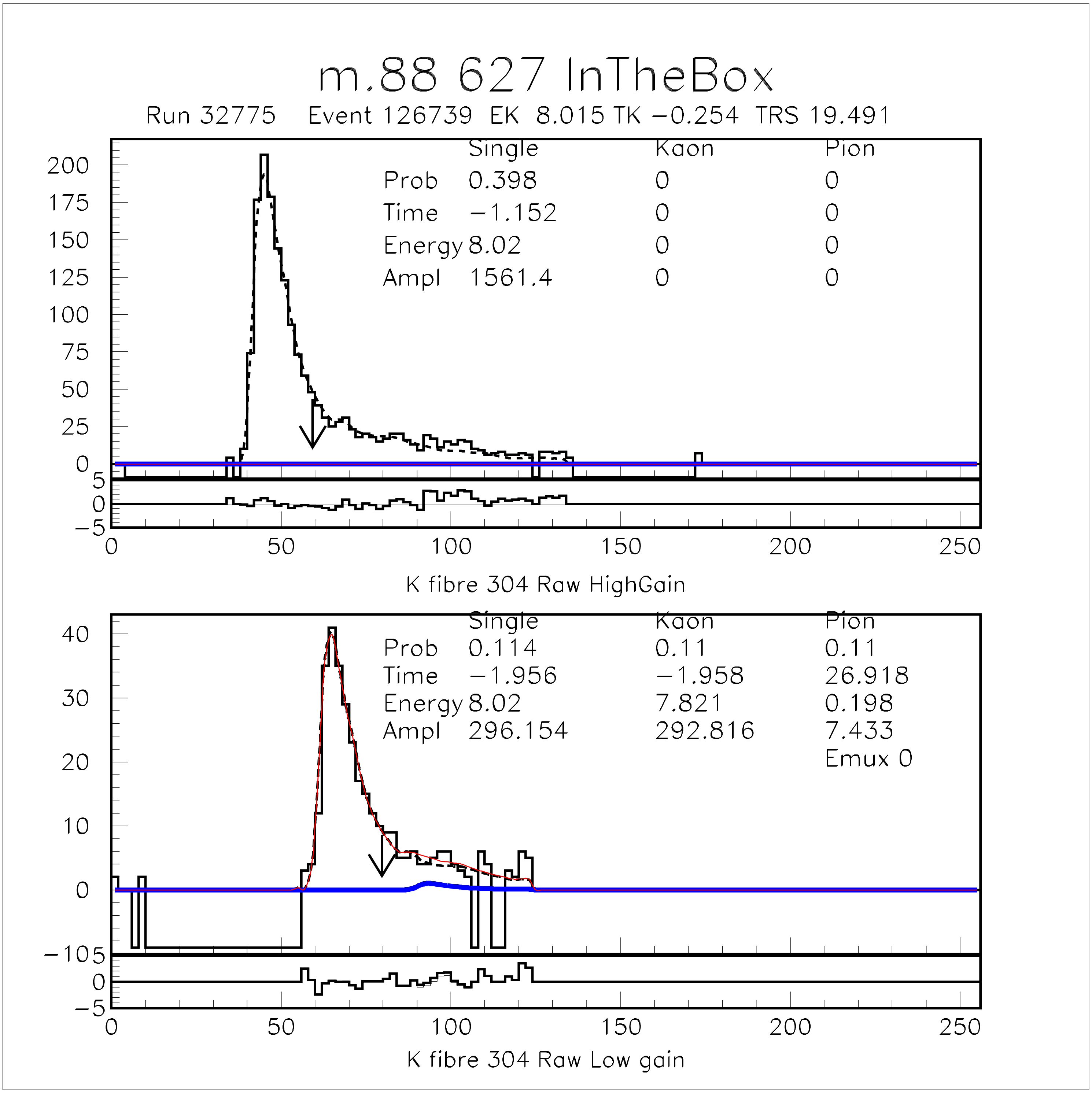
m.88 627 InTheBox
bm
V5, −1, 2
U6, −2.1, 2.3
rs
10
8
6
4
2
0
−2
−4
−6
−8
−10
−10
−8
−6
−4
−2
0
2
4
6
8
10


m.88 627 InTheBox
Top View
bm
rs
BWPC1
BWPC2
B4
Side View
bm
rs
BWPC1
BWPC2
B4
10
8
6
4
2
0
−2
−4
−6
−8
−10
−200
−175
−150
−125
−100
−75
−50
−25
0
25
50

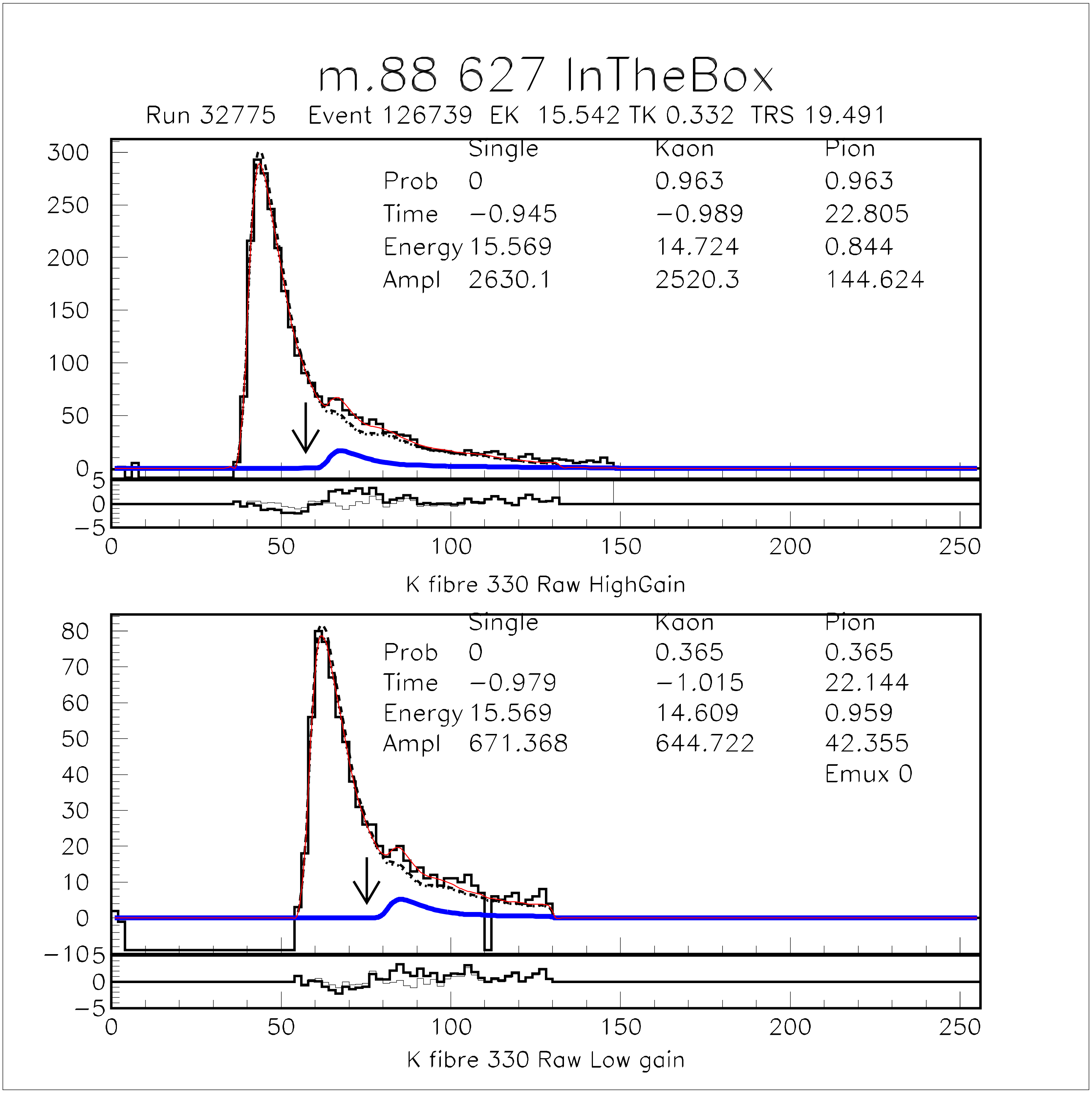

m.88 627 InTheBox
Ck5, −0.8, 15.9
Ck6, −1, 15.9
Ck3, −1.4, 15.9
Ck7, 3.6, 0
Ck2, 0.7, 0
Ck8, −1, 0
Ck1, 0, 0
Ck9, 0.9, 0
Ck14, 0.8, 0
Ck13, −1.7, 15.9
Ck12, −1.2, 18
15
10
5
0
−5
−10
−15
−15
−10
−5
0
5
10
15

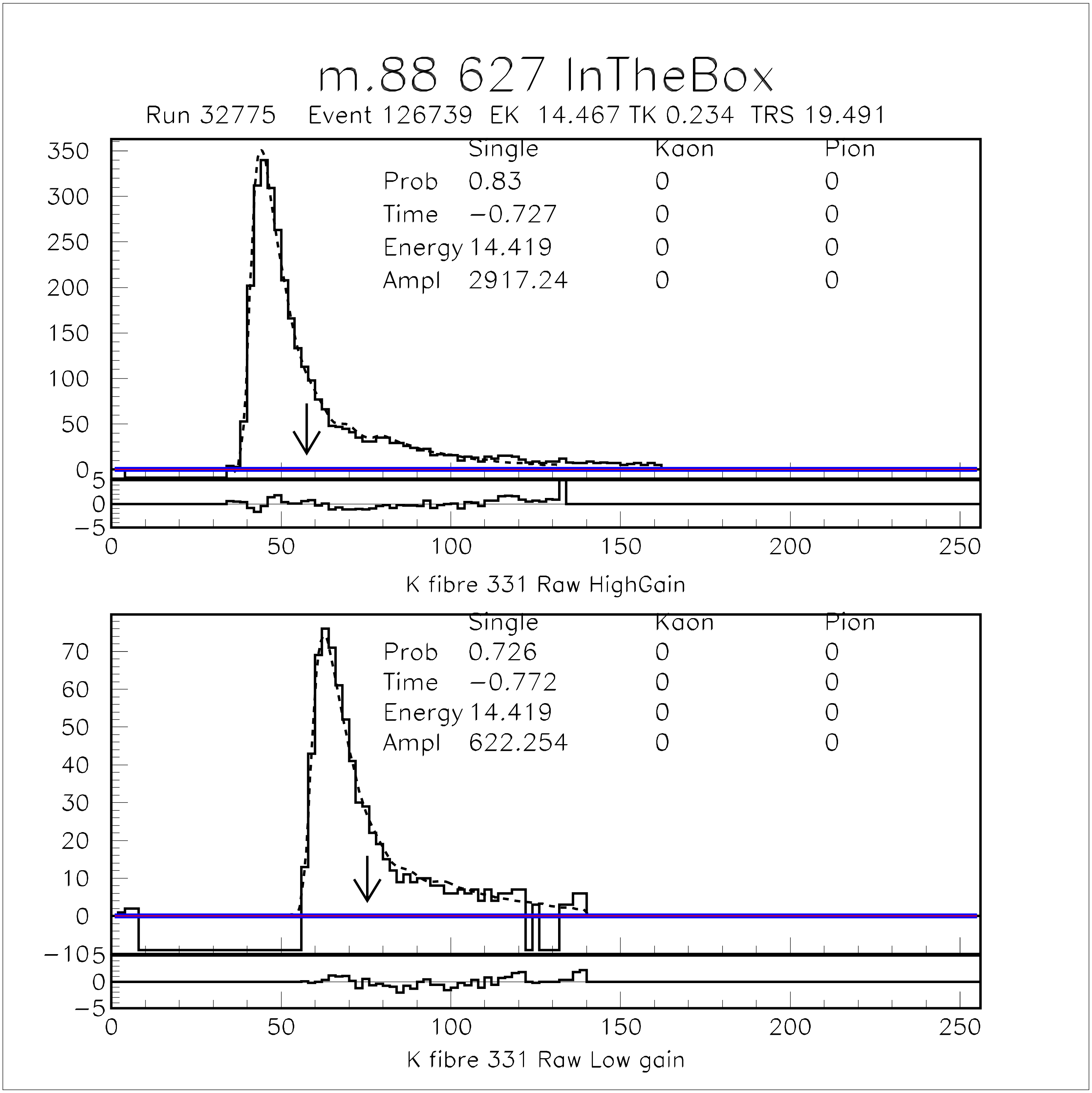


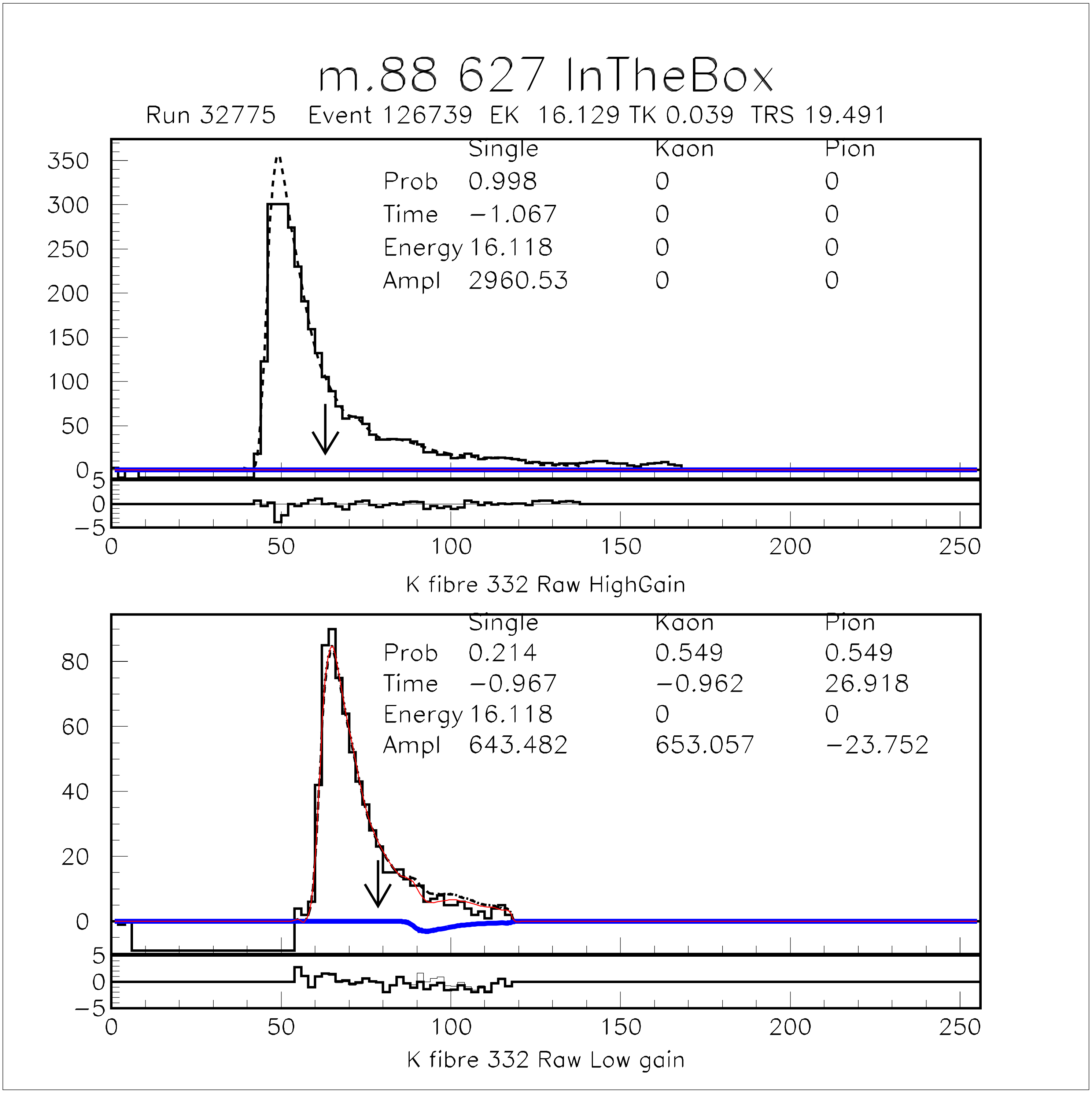
m.88 627 InTheBox
Run 32775 Event 126739 EK 18.475 TK 0.43 TRS 19.491
Single Kaon Pion
Prob 0.938 0 0
Time −0.63 0 0
Energy 18.489 0 0
Ampl 3130.1 0 0
K fibre 329 Raw HighGain
Single Kaon Pion
Prob 0.985 0 0
Time −0.951 0 0
Energy 18.489 0 0
Ampl 667.687 0 0
K fibre 329 Raw Low gain

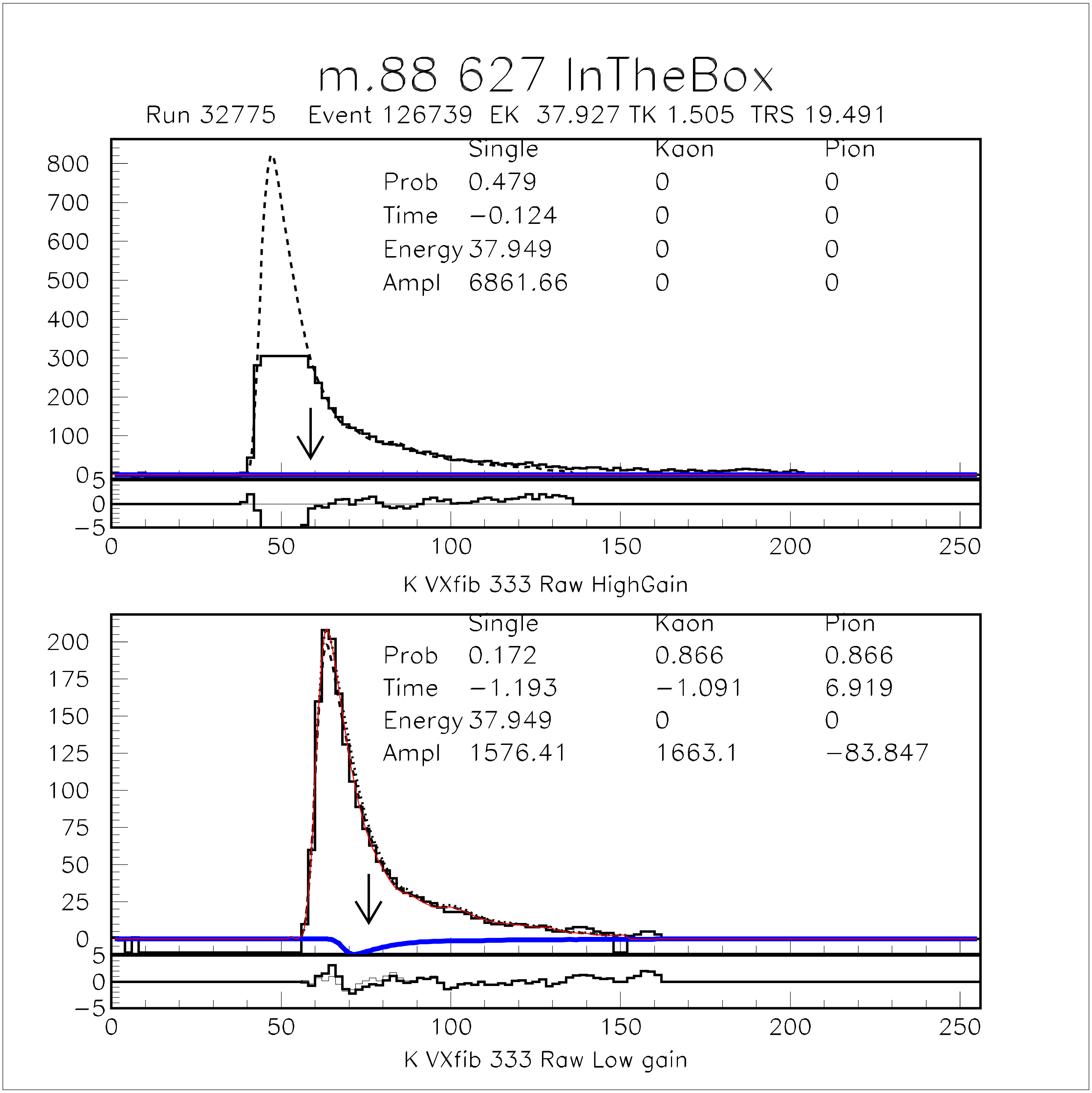


m.88 627 InTheBox
Run 32775 Event 126739 EK 8.015 TK −0.254 TRS 19.491
Single Kaon Pion
Prob 0.398 0 0
Time −1.152 0 0
Energy 8.02 0 0
Ampl 1561.4 0 0
K fibre 304 Raw HighGain
Single Kaon Pion
Prob 0.114 0.11 0.11
Time −1.956 −1.958 26.918
Energy 8.02 7.821 0.198
Ampl 296.154 292.816 7.433
Emux 0
K fibre 304 Raw Low gain


m.88 627 InTheBox
Run 32775 Event 126739 EK 15.542 TK 0.332 TRS 19.491
Single Kaon Pion
Prob 0 0.963 0.963
Time −0.945 −0.989 22.805
Energy 15.569 14.724 0.844
Ampl 2630.1 2520.3 144.624
K fibre 330 Raw HighGain
Single Kaon Pion
Prob 0 0.365 0.365
Time −0.979 −1.015 22.144
Energy 15.569 14.609 0.959
Ampl 671.368 644.722 42.355
Emux 0
K fibre 330 Raw Low gain


m.88 627 InTheBox
Run 32775 Event 126739 EK 14.467 TK 0.234 TRS 19.491
Single Kaon Pion
Prob 0.83 0 0
Time −0.727 0 0
Energy 14.419 0 0
Ampl 2917.24 0 0
K fibre 331 Raw HighGain
Single Kaon Pion
Prob 0.726 0 0
Time −0.772 0 0
Energy 14.419 0 0
Ampl 622.254 0 0
K fibre 331 Raw Low gain


m.88 627 InTheBox
Run 32775 Event 126739 EK 16.129 TK 0.039 TRS 19.491
Single Kaon Pion
Prob 0.998 0 0
Time −1.067 0 0
Energy 16.118 0 0
Ampl 2960.53 0 0
K fibre 332 Raw HighGain
Single Kaon Pion
Prob 0.214 0.549 0.549
Time −0.967 −0.962 26.918
Energy 16.118 0 0
Ampl 643.482 653.057 −23.752
K fibre 332 Raw Low gain


m.88 627 InTheBox
Run 32775 Event 126739 EK 37.927 TK 1.505 TRS 19.491
Single Kaon Pion
Prob 0.479 0 0
Time −0.124 0 0
Energy 37.949 0 0
Ampl 6861.66 0 0
K VXfib 333 Raw HighGain
Single Kaon Pion
Prob 0.172 0.866 0.866
Time −1.193 −1.091 6.919
Energy 37.949 0 0
Ampl 1576.41 1663.1 −83.847
K VXfib 333 Raw Low gain

Acceptance

Acceptance factors	PNN1	PNN2
K^+ stop efficiency	0.702	0.670
K^+ decay after 6 ns	0.851	0.591
$K^+ \to \pi^+ \nu \bar{\nu}$ phase space	0.155	0.345
Geometry	0.409	0.317
π^+ nucl. int. and decay in flight	0.527	0.708
Reconstruction efficiency	0.969	0.957
Other kinematic cuts	0.554	0.686
$\pi - \mu - e$ decay chain	0.392	0.545
Beam and target analysis	0.706	0.479
CCD acceptance	1.0	0.401
Accidental loss	0.751	0.363
Total acceptance	1.96×10^{-3}	7.65×10^{-4}

Acceptance factors used in the measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ in Region 2. The "K^+ stop efficiency" is the fraction of kaons entering the TG that stopped. "Other kinematic constraints" include particle identification cuts.

Total Analysed Exposure:

PNN1: 5.9×10^{12} kaons

PNN2: 1.12×10^{12} kaons

Limits, etc.

- Previous 90% C.L. limit using the low momentum region: 1.7×10^{-8}
  M.S. Atuya et al., Phys. Rev. D 48, R1 (1993).
- E787 measurement using 2 events in high momentum region:

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$$

  S. Adler et al., Phys. Rev. Lett. 88, 041803 (2002).
- This measurement

$$S.E.S = 1.17 \times 10^{-9}$$

- 1 event observed with background of 0.73 ± 0.18.

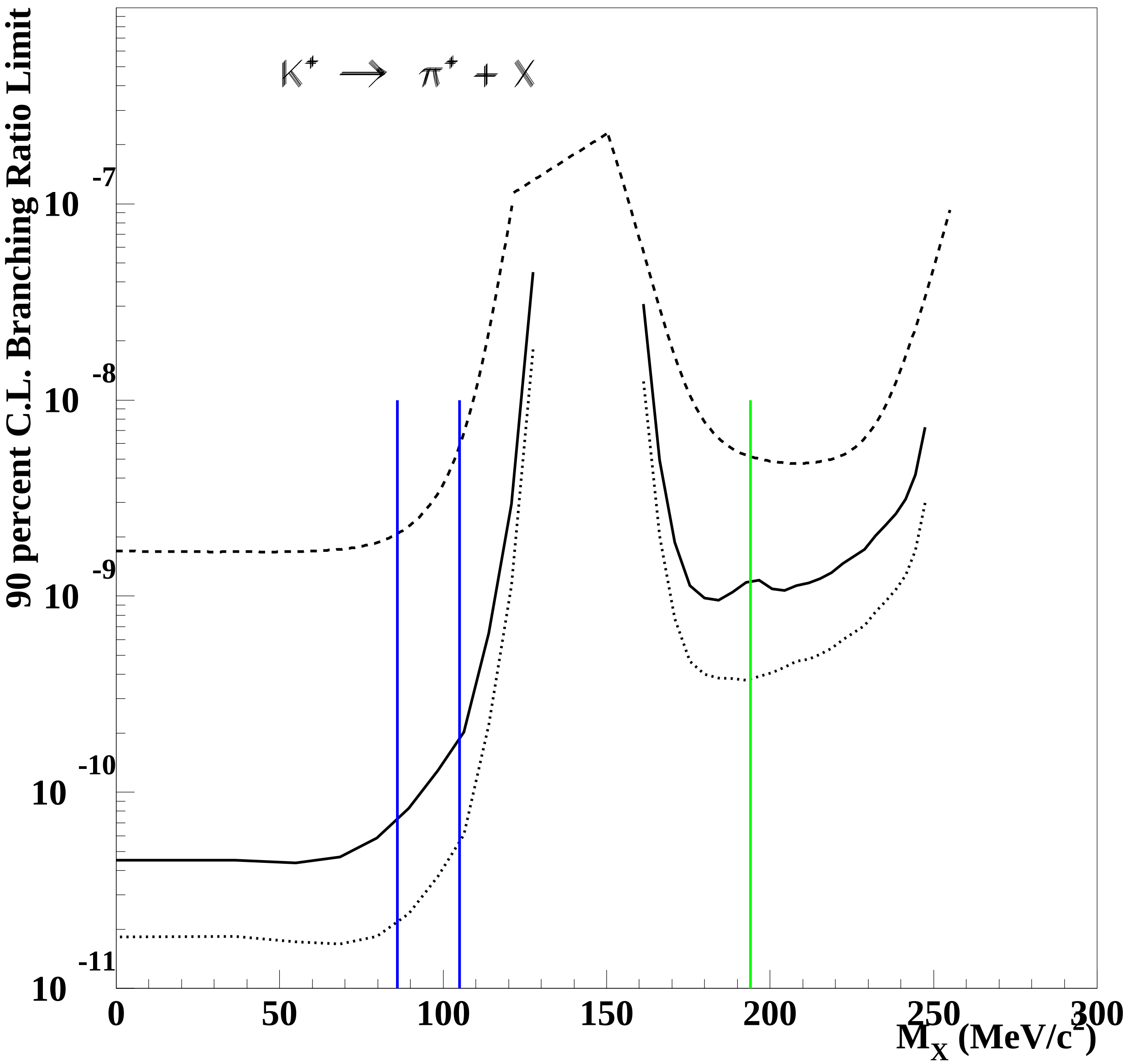
$$B(K^+ \to \pi^+ \nu\bar{\nu}) < 4.2 \times 10^{-9}$$

- Assume Scalar spectrum:

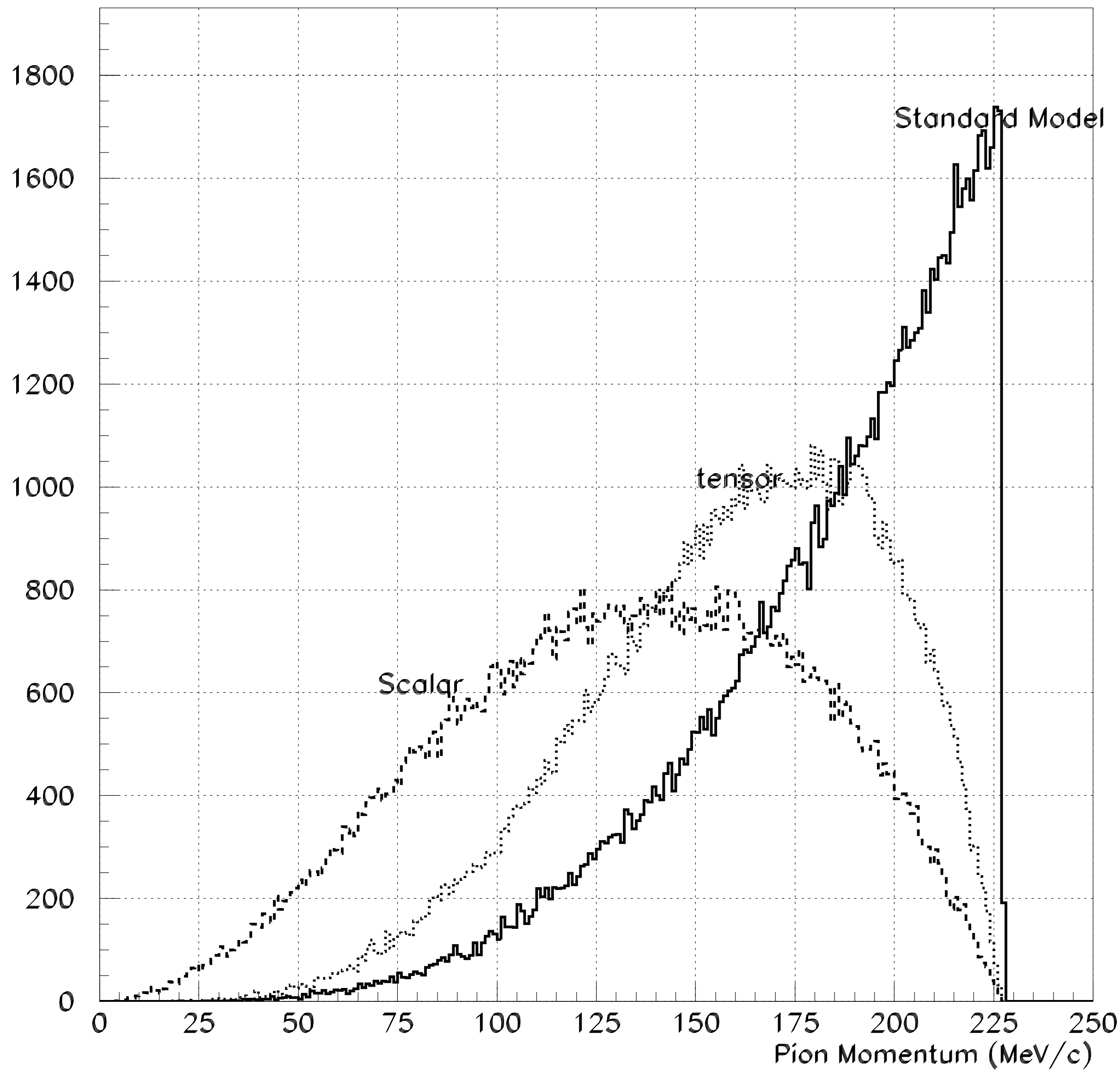
$$B(K^+ \to \pi^+ \nu\bar{\nu})_S < 4.7 \times 10^{-9}$$

- Assume Tensor spectrum:

$$B(K^+ \to \pi^+ \nu\bar{\nu})_T < 2.5 \times 10^{-9}$$

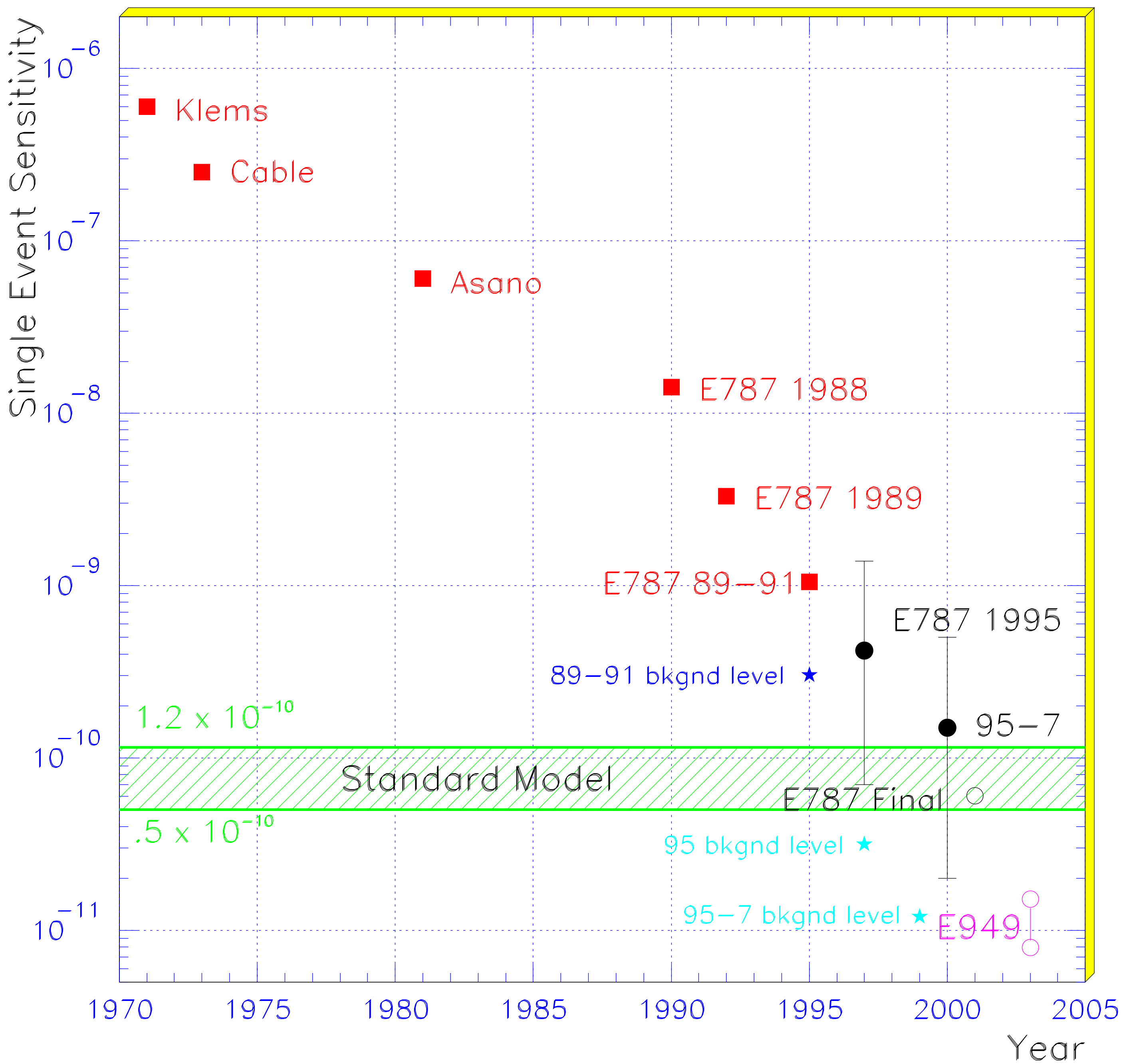


$K^+ \rightarrow \pi^+ + X$
90 percent C.L. Branching Ratio Limit
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0
50
100
150
200
250
300
M_X (MeV/c^2)



Milind V. Diwan

Progress in $K^+ \to \pi^+ \nu \bar{\nu}$



Conclusion

- Analysis of E787 PNN1 data from 95-98 complete with result of

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$$

- Major new effort on analysis of PNN2 (below the Kpi2 peak) concluded.

  1 event observed with background of 0.73 ± 0.18.

$$B(K^+ \to \pi^+ \nu\bar{\nu}) < 4.2 \times 10^{-9}$$

- New techniques using the fiber-target and CCDs allow background determination in PNN2 region.

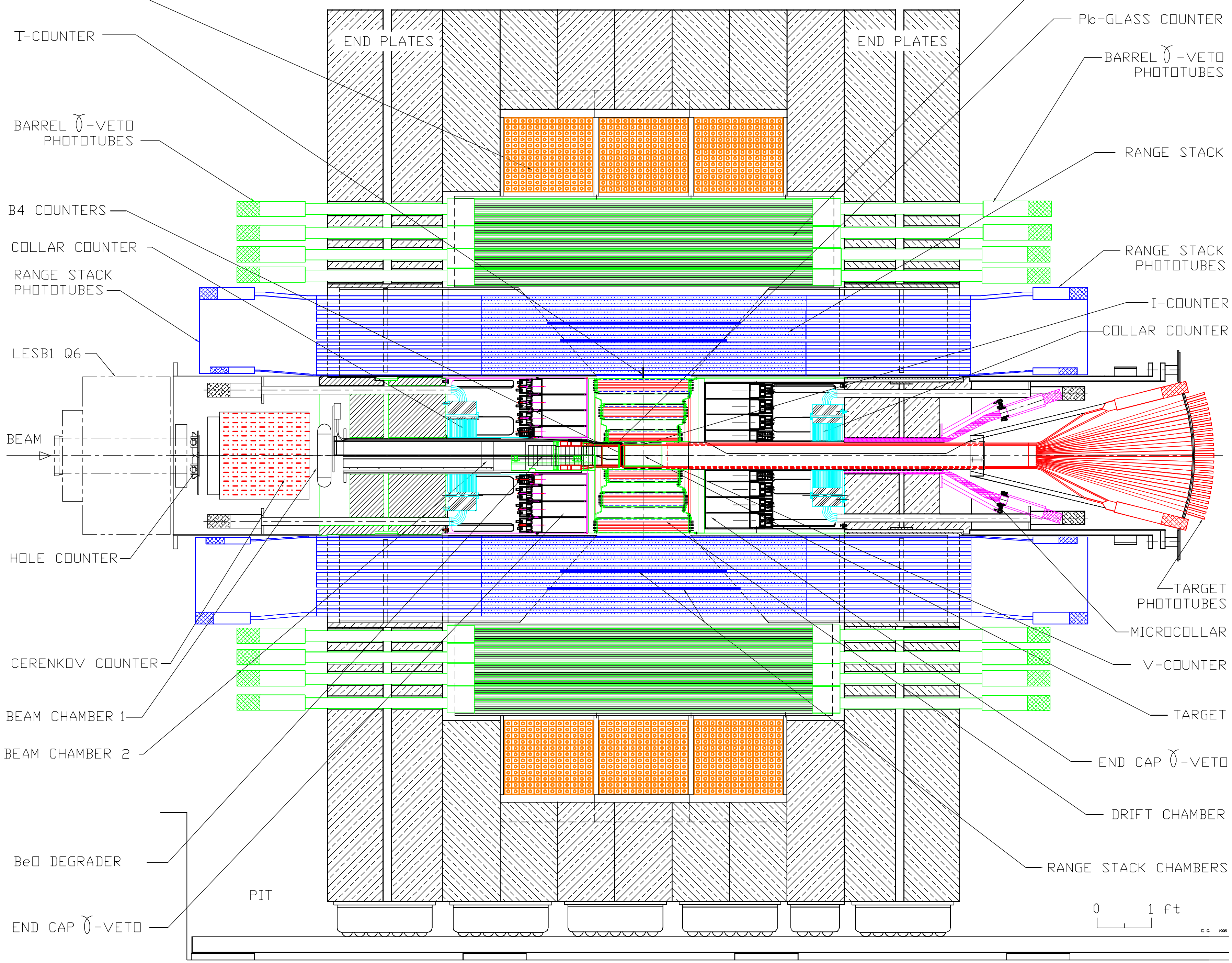
  No evidence of major background other than KPI2.

- The PNN2 measurement appears to be limited by photon veto.

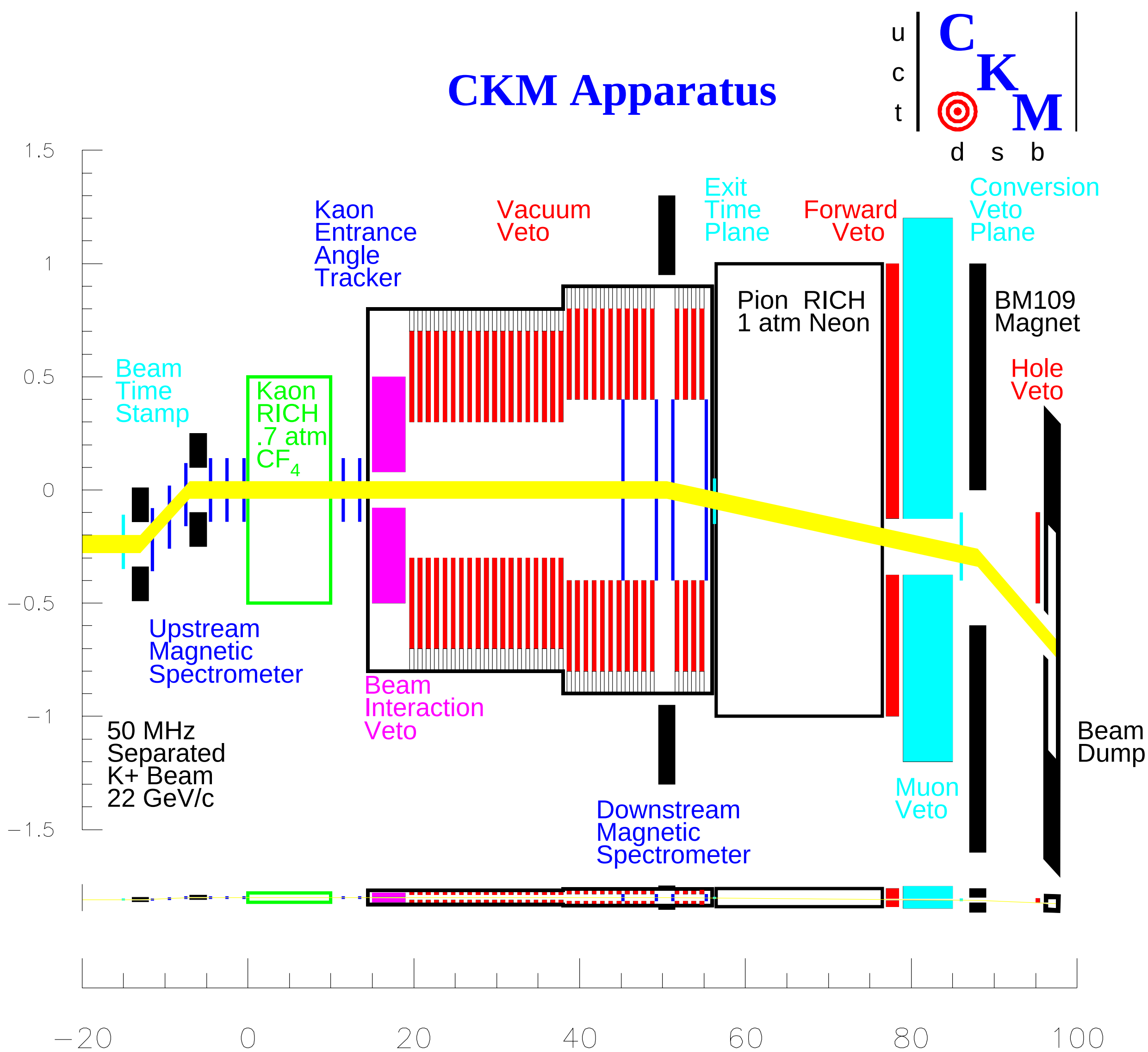
- E949 with major upgrades to photon veto system and many other improvements on schedule to take $\times 10$ data.

- FNAL experiment CKM may have no scattering background. Could be best place to do low momentum measurement.

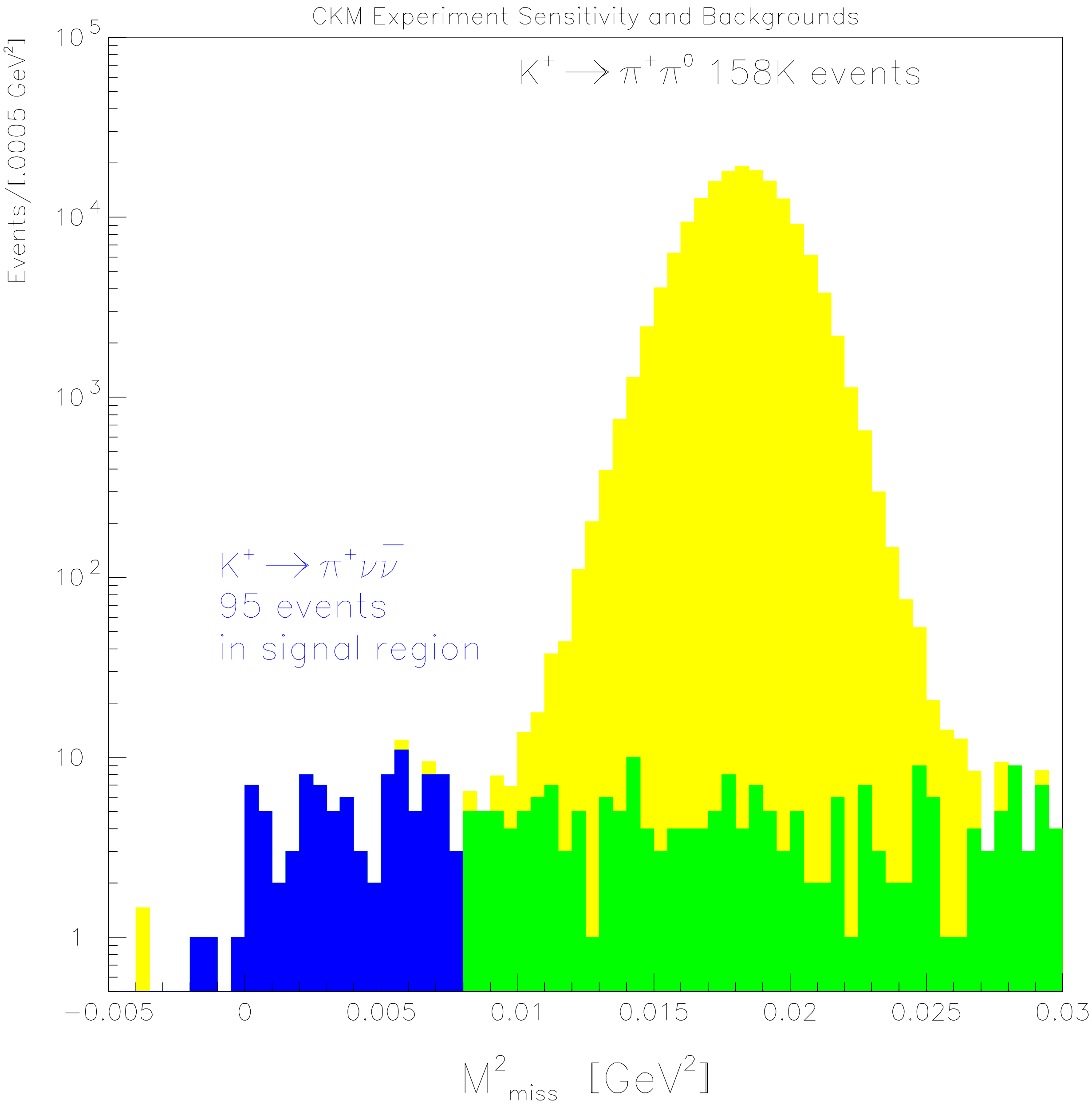
E787 DETECTOR



CKM in brief



CKM Apparatus
u
c
t
C
K
M
d s b
1.5
1
0.5
0
−0.5
−1
−1.5
Beam Time Stamp
Kaon RICH .7 atm CF_4
Kaon Entrance Angle Tracker
Vacuum Veto
Exit Time Plane
Forward Veto
Conversion Veto Plane
Pion RICH 1 atm Neon
BM109 Magnet
Hole Veto
Upstream Magnetic Spectrometer
50 MHz Separated K+ Beam 22 GeV/c
Beam Interaction Veto
Downstream Magnetic Spectrometer
Muon Veto
Beam Dump
−20
0
20
40
60
80
100



CKM Experiment Sensitivity and Backgrounds
Events/[.0005 GeV²]
$K^+ \rightarrow \pi^+\pi^0$ 158K events
$K^+ \rightarrow \pi^+\nu\bar{\nu}$
95 events
in signal region
10^5
10^4
10^3
10^2
10
1
−0.005
0
0.005
0.01
0.015
0.02
0.025
0.03
M^2_{miss} [GeV²]